Real-Time Hair Rendering

Master Thesis

Computer Science and Media M.Sc.

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Abstract

An approach is represented to render hair in real-time by using a small number of guide strands to generate interpolated hairs on the graphics processing unit (GPU). Hair interpolation methods are based on a single guide strand or on multiple guide strands. Each hair strand is composed by segments, which can be further subdivided to render smooth hair curves. The appearance of the guide hairs as well as the size of the hair segments in screen space are used to calculate the amount of detail, which is needed to display smooth hair strands. The developed hair rendering system can handle guide strands with different segment counts. Included features are curly hair, thinning and random deviations. The open graphics library (OpenGL) tessellation rendering pipeline is utilized for hair generation.

The hair rendering algorithm was integrated into the Frapper's character rendering pipeline. Inside Frapper, configuration of the hair style can be adjusted. Development was done in cooperation with the Animation Institute of Filmakademie Baden-Württemberg within the research project "Stylized Animations for Research on Autism" (SARA).

Keywords: thesis, hair, view-dependent level of detail, tessellation, OpenGL, Ogre, Frapper

Declaration of Originality

Markus Rapp, 7. November 2014

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I also want to say thank you to my family, who supported me financially over my whole study time.

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Contents

1. Introduction

Real-time hair rendering has been a huge challenge in the games industry and for simulation applications. On a human head are up to 150000 hairs. Main challenge is to be able to render this huge amount of hair strands in real-time. With modern graphics processors it becomes possible to render thousands of hair strands on the GPU. How can modern graphics cards be utilized for hair rendering? Is it possible today to render realistic hair in real-time?

These questions were answered within the research project SARA for Institute of Animation of Filmakademie Baden-Württemberg. The official name of the project is "**Impact of non-photorealistic rendering for the understanding of emotional facial expressions by children and adolescents with high-functioning Autism Spectrum Disorders**". The project deals with the creation and animation of computer-generated facial expressions in different levels of abstraction for the purpose of investigating how these different facial expressions are perceived by subjects with Attention-Deficit/Hyperactivity Disorder (ADHD) and Autism Spectrum Disorders (ASD). Filmakademie Baden-Württemberg cooperates for this research project with University of Konstanz and University Hospital Freiburg. The project is funded by DFG.

One area of the project is the rendering of realistic hair in real-time. For hair rendering there is already an implementation. The implementation uses predefined geometry. For every single hair strand vertices, normals, tangents and texture coordinates are stored in a mesh file. This leads to a huge amount of data, which needs to be loaded, transferred to GPU memory and rendered.

Target of this thesis is to research different techniques to reduce the amount of data that needs to be stored and to increase the frame rate for rendering the virtual character. It is investigated how hair geometry can be directly generated on the GPU. The idea is to use a small number of guide strands and generate new hair strands out of these guides. Techniques are compared, which use a single guide strand as well as multiple guide strands as input. Different distribution patterns and randomization techniques for the position of hair and shape of hair are tried out. It is investigated how level of detail (LOD) techniques can be utilized to be able to render smooth hair strands and at the same time save processing resources for an increased frame rate. Additionally, hair shading techniques are evaluated for rendering of realistic hair.

Related work, which already has been done in real-time hair rendering is analysed in section 2. Afterwards, requirements for the development of the hair rendering system are described. In section 4 the features and functionality OpenGL tessellation rendering pipeline are shown. Section 5 focuses on the implementation of the hair rendering system. Topic in section 6 is the integration of the developed hair rendering system into the character rendering system of the Frapper framework. In the following section the performance of the developed hair rendering system is tested and compared against related work. The final section concludes this thesis and points out possible areas of future research.

2. Related Work

In the past, real-time hair rendering could only be done with a mesh representation of the hair on which a material was applied.

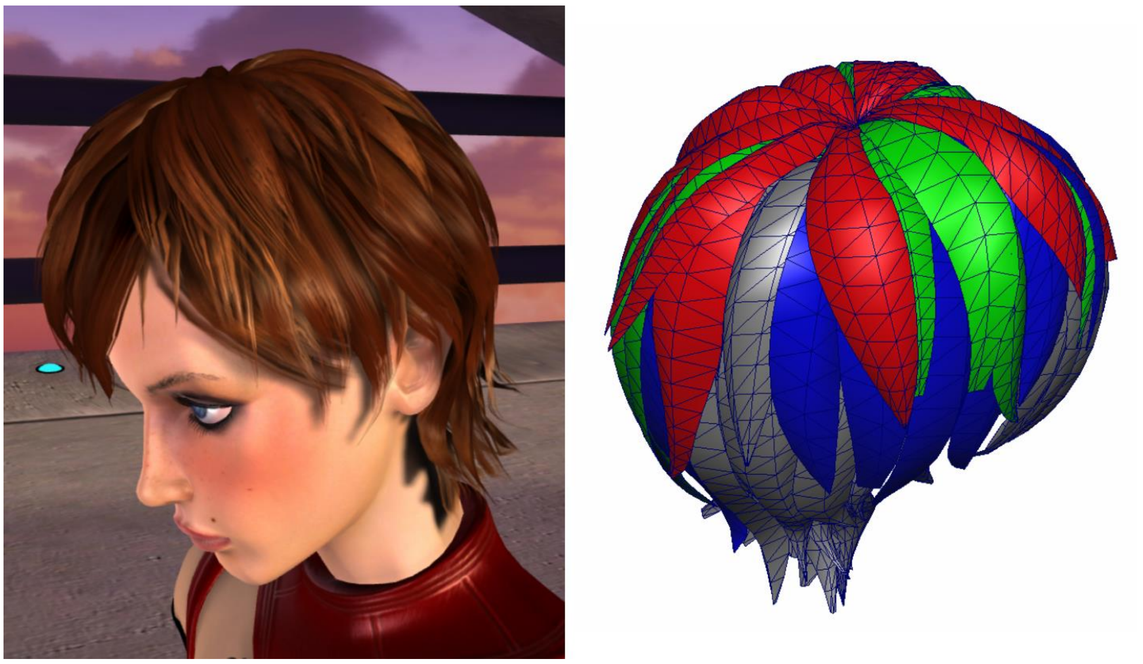


Figure 1: Hair rendering of Ruby by [Scheuermann 2004]

One attempt to put hair on a human mesh was done by [Scheuermann 2004] of ATI Research and presented at Siggraph 2004. Scheuermann's approach is based on the hair shading model of [Kajiya and Kay 1989] and specular highlights model of [Marschner et al. 2003]. The hair model consisted of two-dimensional (2D) layered polygon patches with a main texture for the structure and an opacity map for the diversity of the hair. 2D layered polygon patches were used instead of lines because they have a low geometric complexity, which reduced load for the vertex shader. Shading was done with a diffuse lighting term, two specular highlights and ambient occlusion. The first specular highlight is the direct reflection of the light. The second specular highlight is transmitted into the hair in direction of the root and internally reflected back to the viewer. As a result, the colour of the second specular highlight is modulated by the hair colour and the shape of the highlight is depolarized. Additional calculations need to be executed for depth sorting, which is done entirely on the GPU. Four render passes are needed for this operation. This hair technique was used by ATI for their Ruby demo "The Assassin".

In 2004 [Nguyen and Donnelly 2004] developed the Nalu Demo for the NVIDIA Geforce 6800 launch. Their target was to render realistic hair in real-time. The hair of Nalu was long, blond and needed to flow underwater. 4095 individual hairs were represented as line primitives. These lines had a total of 123000 vertices. However, this number of hairs was too huge for dynamics and collision detection calculations. The solution was to use hundreds of control hairs instead. Segments of the control hair did not have a uniform length. Segments near to the hair root were short and further away from the root were longer. This allowed to render long hairs with a smaller vertex count. A scalp mesh defined the roots of the control hairs.

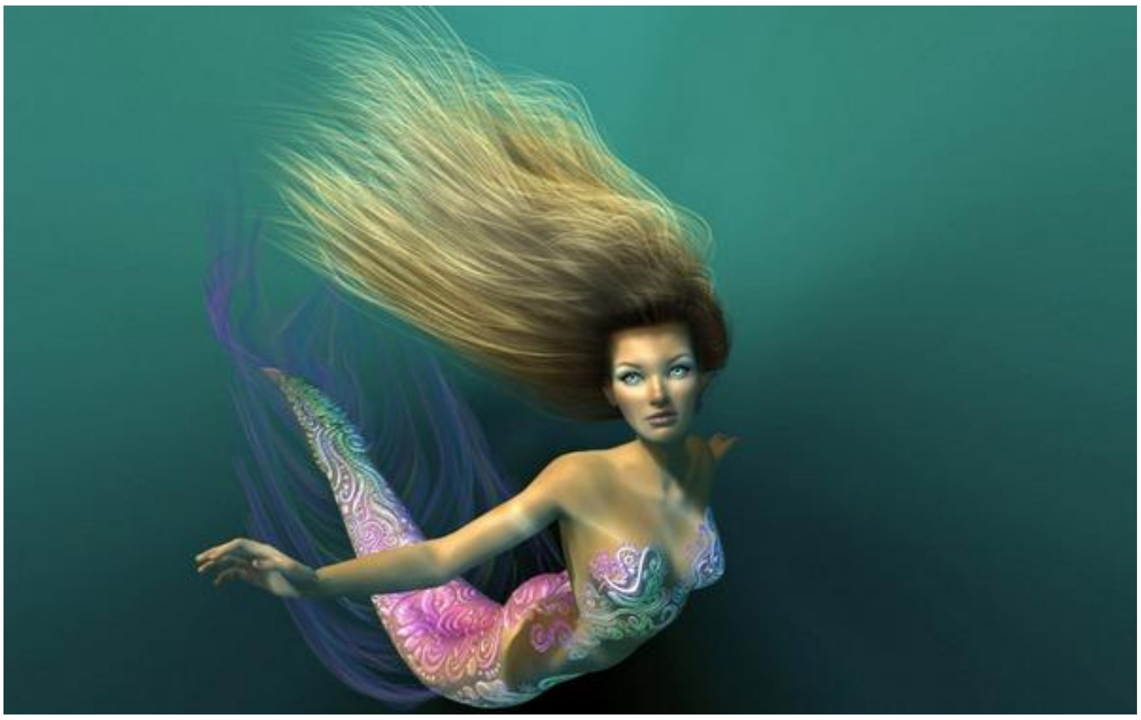


Figure 2: Screenshot of NVIDIA Nalu demo [NVIDIA 2004]

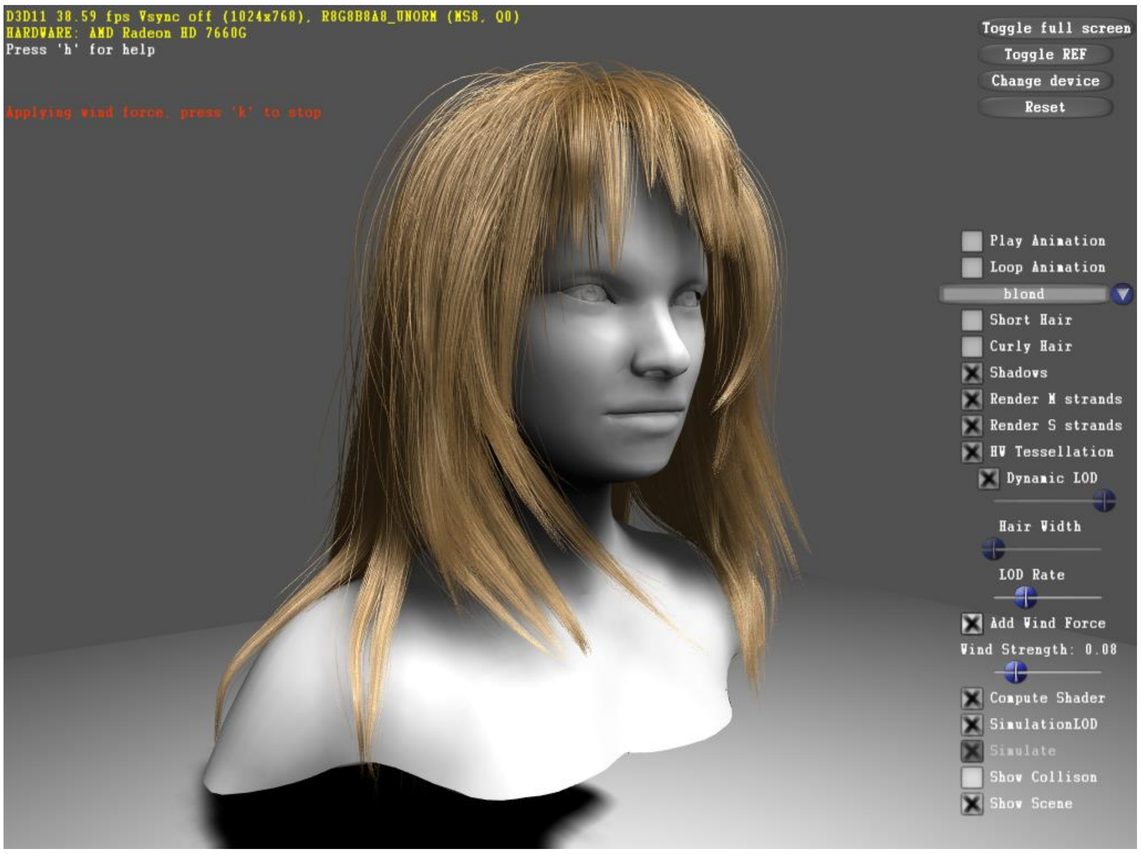
For every render pass tangents of the control hairs were calculated. The lines were converted into Bézier curves and tessellated to get smooth lines. These smoothed lines were interpolated to increase the hair density. For interpolation three control hairs were selected according to their position in the scalp mesh. Barycentric interpolation was used to calculate a new vertex position out of three vertex positions of the guide hairs. The barycentric coefficients were random generated, which gave a random distribution of hair strands within the scalp mesh triangle. The result hair had the same number of vertices as the guide hairs. A dynamic vertex buffer was used to hold the vertex data.

Dynamics and collision computations were based on a particle system, where every control hair vertex represented one particle. Distance constraints between particles were used to control the hair length. Hair segment repelled when they were too close to each other and contracted if they were too far apart. Collision was done only with spheres. Spheres represented the head and upper body of Nalu as well as every vertex of the guide strands.

For the local reflectance model of the hair, the lighting model of [Marschner et al. 2003] was used, which describes how hair fibres scatter and reflect light. The hair fibre is described as a translucent cylinder. Three possible paths that light may take through the hair are considered. The first is a direct reflection of the light, which bounces of the surface. In the second path light is refracted into the hair and refracted out again. In the third case light refracts into the hair, is reflected inside the surface of the hair and refracted out of the hair. [Nguyen and Donnelly 2004] also considered self-shadowing of the hair. For this purpose they used opacity shadow maps, which were developed by [Kim and Neumann 2001].

2.1. NVIDIA Fermi Hair Demo 2008

Sarah Tariq implemented an impressive real-time hair simulation and rendering demo based on the work of the NVIDIA Nalu Demo. The demo with source code was published at [NVIDIA 2010b]. Papers and presentations about Sarah Tariq's work are available at [Tariq and Bavoil 2008b; Tariq 2010c; Yuksel and Tariq 2010; Tariq and Bavoil 2008a; Tariq 2010d, 2010b, 2010a, 2008].


```
D3D11 38.59 fps Vsync off (1024x768), R8G8B8A8_UNORM (MS8, Q0)
HARDWARE: AMD Radeon HD 7660G
Press 'h' for help

Applying wind force, press 'k' to stop
```

☐ Play Animation
☐ Loop Animation
blond
☐ Short Hair
☐ Curly Hair
☒ Shadows
☒ Render M strands
☒ Render S strands
☒ HW Tessellation
☒ Dynamic LOD
Hair Width
LOD Rate
☒ Add Wind Force
Wind Strength: 0.08
☒ Compute Shader
☒ SimulationLOD
☒ Simulate
☐ Show Collison
☒ Show Scene

Figure 3: NVIDIA Fermi Hair Demo screenshot [NVIDIA 2010b]

The hair demo uses 166 simulated hair strands. The rest of the hairs are generated and interpolated on the GPU with two different interpolation patterns called single strand and multi strand interpolation.

Single strand interpolation uses one guide hair. The interpolated hair has the same shape as the guide hair and is placed with a random offset in two directions in a plane that is perpendicular to the guide strand. A predefined maximum radius is set to control the maximum distance of the interpolated strand to the guide strand. Single strand interpolated hair results into a clumpy hair style. For the given 166 guide strands up to 10624 strands can be generated on the GPU.

Multi strand interpolation works the same way as in [Nguyen and Donnelly 2004]. The interpolated strand is created by linearly interpolating the attribute of three guide strands, which are selected according to the triangle vertices of a scalp mesh. Coefficients values for barycentric interpolation are generated randomly. Result of this interpolation scheme is a uniform look. The number of strands that can be generated is dependent on the face number of the scalp mesh. The demo scalp mesh consists of 294 faces, which allow up to 18816 hair strands generated on the GPU with a single draw call.

Hair geometry is rendered as camera facing quads. The problem with rendering lines is that the width of lines can only be changed per draw call. Width of hair segments need to be different to be able to render hair strands with varying width towards the hair tip. Varying width would only be possible for lines with multiple draw calls. A draw call is an expensive operation and the number of draw calls should be minimized. Therefore rendering lines with multiple draw calls is bad for performance. Additionally, a flexible hair segment width is needed for level of detail operations. Furthermore, it is not possible to apply textures to lines. Camera facing quads can be textured and have a real world width. It is also possible to taper hair towards its end with camera facing quads. However, rendering quads is more expensive than rendering lines. All calculation prior to rendering like simulation, tessellation and interpolation, are done with lines. In the geometry shader those calculated lines are expanded to camera facing quads.

The hair demo utilizes the tessellation rendering engine of modern GPUs, which is perfect for the creation of large amounts of data on the GPU. The main bottleneck is the bandwidth between central processing unit (CPU) and GPU. It is faster creating data on the GPU than uploading data from the CPU to the GPU. It is also possible to have a fine grained and continuous level of detail with the tessellation engine.

The demo also works with DirectX 10 capable graphic cards. The geometry shader is not used for the generation of hair because it would be extremely inefficient. The geometry shader is optimized for relatively small amounts of data expansion. A good use case for the geometry shader is to expand lines to camera facing quads. This raises the question how it is possible to generate geometry without the tessellation engine and the geometry shader? The idea is to render dummy hair strands with empty vertex and index buffer. A line strip render call with a vertex count of $m*n$ needs to be executed, where m stands for the maximum number of vertices per strand and n is the number of interpolated strands to render. Rendering for this operation is reasonably fast because there are no real attributes used. The evaluation of vertex attributes can be done in the vertex shader. Guide strand attributes are stored into textures or buffers. Stored data are length, width and vertex positions of the guide strands. The GPU uses a different vertex index (ID) for each call of the vertex shader, which allows to select the right vertex attributes of the strand segment that needs to be rendered.

The implementation with the tessellation engine compared to the DirectX 10 implementation is faster, easy and intuitive, more programmable, supports continuous level of detail, and the tessellation engine saves memory and bandwidth. The DirectX 11 tessellation engine introduces three new shader stages, the hull shader, the tessellator and the domain shader, which are placed between the vertex shader and the geometry shader in the DirectX 11 shader pipeline. For the tessellation engine the isoline domain was used. The hardware tessellator creates for each patch a number of isolines with multiple line segments per line. A patch with a single control point was used as primitive topology. In the hull shader is calculated how many lines are generated and how many segments per line are tessellated. There is a hardware limitation for how many lines and line segments can be generated with the tessellation engine. Per patch a maximum of 64 isolines with 64 segments can be created. The hull shader allows to calculate the level of detail per line segment.

In the Fermi Hair Demo the level of detail is dependent on the distance of the camera to the head. With a higher distance less hair strands with a thicker width are generated. This is done to achieve no visible reduction in density of hair and at the same time save computing resources for rendering. A density map and thickness map were used for a more precise level of detail. Artists can define in the density map, which areas of the scalp should have a high density of generated hairs. This allows to use the limited computing resources at places of the scalp, where it is most important to show hairs. In the thickness map it can also be defined how thick the hair should be. The final positions of the line segments vertices are calculated in the domain shader.

Following steps are performed for hair rendering. First, the guide hairs are imported. Every frame, guide hairs are simulated, tessellated, interpolated and rendered. Shading operation and shadow calculations are executed for the final rendering of the hair. These multiple operations have to be divided in multiple render stages. At the end of each stage, data is streamed out to the next stage to minimize re-computation. In the first stage, simulated guide strands are tessellated and streamed out. These tessellated strands are interpolated in the next stage. Afterwards, the final hair is rendered for shading into shadow maps. The last stage is to render the final hair to the screen.

The guide hairs are smoothly tessellated with uniform cubic b-splines, which automatically handle continuity. To tessellate hair strands with uniform cubic b-splines four vertices of the strand are needed per patch. The end points of the guide hair need to be repeated because uniform cubic b-splines do not interpolate the endpoints.

It is also possible to render curly hair in the demo. Therefore, additional curl offsets are pre-computed and encoded. The result is stored in a buffer or a texture. Curl offsets can be created procedurally as in the demo. It is also possible that artists create these curl offsets manually.

Another important feature of the NVIDIA hair demo is random variations between hair strands. Without this feature hair looks smooth and synthetic. Randomness is applied when hair is interpolated. Two types of deviations are defined. The first type is small deviations near the tips, which is applied to 30% of the hair strands. The second type is applied to 10% of the hair strands and produces deviations along the whole strand.

Hair simulation is another important part of hair rendering. All simulations are done on a small number of guide strands. Tariq used a particle constraint system. All guide strand hair vertices are simulated as particles. Three constraints are applied for simulation: distance, collision and angular forces constraint. With the distance constraint length of hair is maintained, which prevents hair from stretching and compressing. The angular forces constraint maintains the shape of the hair. The collision constraint keeps hair outside of collision obstacles and handles collision between guide hair strands.

Those constraints are applied in parallel. Two constraints can be updated in parallel only if they are independent of each other. In case of hair segments this means that they share no vertex. The solution to be able to calculate constraints in parallel is to subdivide independent constraints into two groups. Calculate the second group after the calculations of the first group are finished.

Hair simulation is calculated entirely on the GPU. In Direct3D 11 the compute shader is used for hair simulation. With the compute shader, code is easier to write and can be faster. All constraints can be satisfied in a single function call using shared memory and all vertices of a single strand are in the same thread group. For the Direct3D 10 implementation GPGPU[1] pingponging technique is used. Constraints are calculated in the geometry shader. The results are written to stream out and can be used at the next rendering pass. Tariq also used a level of detail system for the simulation of the hair. For high level of detail, simulation is done every frame and for low level of detail, simulation is done once every n frames, where n is the number of frames without simulation calculations.

One issue for simulation is that multi strand hair interpolation leads to hair penetration into collision objects. For the solution of this problem it was important that no simulations should be done on the interpolated hair strands. The solution for that problem was to switch to single strand interpolation when it is detected that multi strand

[1] general purpose computing on graphics processing units (GPGPU)

interpolation leads to penetration of collision obstacles. Therefore, all hair strand vertices, which penetrate collision obstacles and all vertices beneath penetration need to change the interpolation mode. First, a pre-pass is executed, where all the interpolated hairs are rendered to a texture. All vertices of an interpolated hair strand are rendered to the same pixel. It is checked for each hair vertex if it collides with a collision obstacle. If a collision occurs, the ID of the hair vertex is saved to the pixel. The ID is the number of vertices that separate the current vertex from the hair root. If no collision happens, output value is a large constant number. Result is a texture that encodes for each interpolated guide strand weather any of its vertices intersect a collision object and at which position of the guide strand the collided vertex is located. For the hair interpolation this texture is used to decide if the interpolation mode has to be switched. For a smoother transition a blending zone is used above the first intersection to blend from multi strand to single strand interpolation.

A problem related with the hair strands is their thinness. This leads to unpleasant aliasing effects when projected onto a screen because they are often much thinner than a pixel. Solution for this problem is antialiasing or render thicker lines with transparency. Light coloured hair is semi-transparent. Handling transparency would also mean an improvement in visual quality. Antialiasing techniques, which can be used are super sampled anti-aliasing (SSAA) or multi sampled anti-aliasing (MSAA). For SSAA the scene is rendered in a higher resolution and down sampled. MSAA is implemented in hardware and therefore very fast. MSAA performs on the pixel shader a depth/stencil test independent of each other. For 4xMSAA the vertex shader is executed once and the depth/stencil test is executed four times. In the demo a combination of 8xMSAA and 2xSSAA was used.

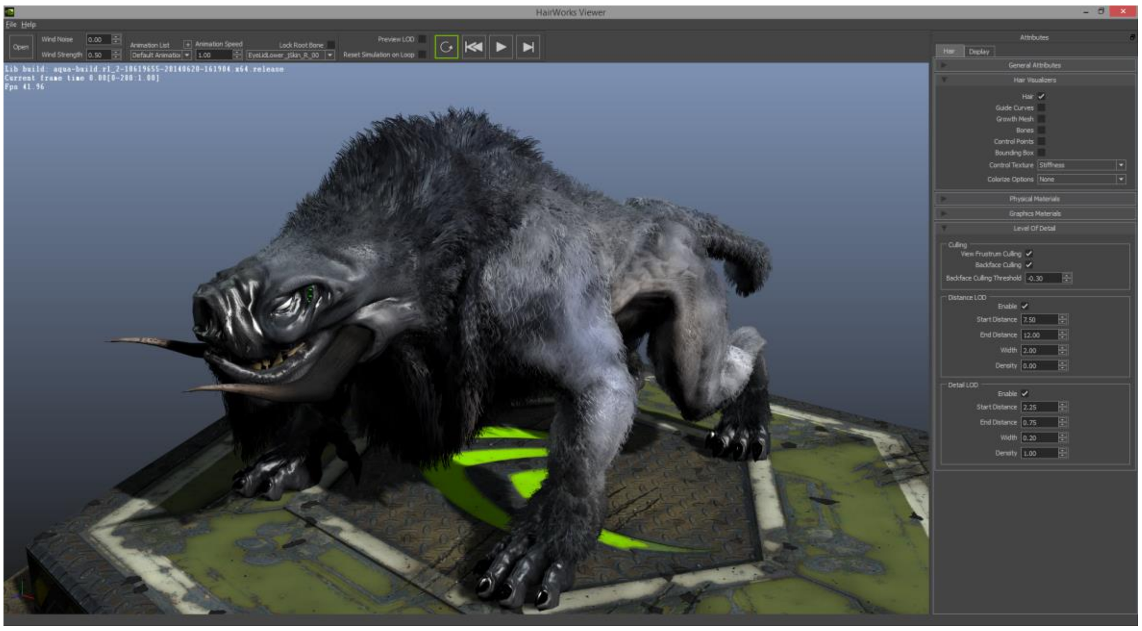
According to Tariq transparency can be done with alpha blending. It hides aliasing. The problem is that the geometry has to be sorted from back to front. This means that every line segment needs to be sorted. If sorting is executed, it should be done on the GPU. Quick sort can be calculated on the GPU. Therefore line segments need to be partitioned and sorted according to their distance to the camera. The geometry shader can be used for this operation. A faster but more complicated algorithm is radix sort. Radix sort can be computed on the GPU using CUDA. Depth sorting can be avoided with fake transparency by dividing the hair into three subgroups and blending the result together. Tariq recommended two approaches. For a performance oriented approach multi-layer fake transparency and MSAA should be used. If quality is the main target alpha blending with GPU sorted line fragments with MSAA is the better solution.

For hair shading it has also an effect that hair strands are very thin. Because of that tangents are used instead of normals. Tangents have to represent the direction of a hair strand segment and have to be smooth. Additionally, jitter and noise is used for tangents to break strong highlights. The used lighting model was [Kajiya and Kay 1989]. It is not completely physical based. The diffuse term integrates lambertian surface along a thin cylinder. The specular term is based on phong using thin cylinders. A physical based alternative would be [Marschner et al. 2003].

Shadows were handled with deep opacity maps of [Yuksel and Keyser 2008b, 2008a]. These volumetric shadow maps are suitable for rendering semi-transparent hair. Deep opacity maps is a real-time, artefact free algorithm, which uses a depth map and one opacity map per layer. The algorithm needs three passes. The first pass is for the creation of the depth map, which is rendered from the position of the light source. The second pass is for the calculation of the opacity map layers. Three layers give a sufficient result. Layer distances can be constant, powers of 2, Fibonacci or linear. The third pass is to render the final image to screen. As an analysis of the source code of [NVIDIA 2010b] has shown, deep opacity maps were not enabled for this demo. Only a simple shadow map is generated, which handles shadowing of the hair for one light source. However, there is source code of the implementation of deep opacity maps available in [NVIDIA 2010b].

The demo reaches 15 frames per second (FPS) with an NVIDIA GeForce 8800 GTX, a resolution of 1280x1024, 8xMSAA, 166 simulated strands, 10220 rendered strands and 1.6 million triangles.

2.2. NVIDIA HairWorks



Wind Noise 0.00
Wind Strength 0.50
Animation Speed 1.00
Default Animation
Lock Root Bone EyeLidLower_JSkin_R_00

```
Lib build: aqua-build.r1_2-18619655-20140620-161904.x64.release
Current frame time 0.00[0-200:1.00]
Fps 41.96
```

Hair ✓
Guide Curves
Growth Mesh
Bones
Control Points
Bounding Box
Control Texture: Stiffness
Colorize Options: None

Culling
View Frustrum Culling ✓
Backface Culling ✓
Backface Culling Threshold -0.30

Distance LOD
Enable ✓
Start Distance 7.50
End Distance 12.00
Width 2.00
Density 0.00

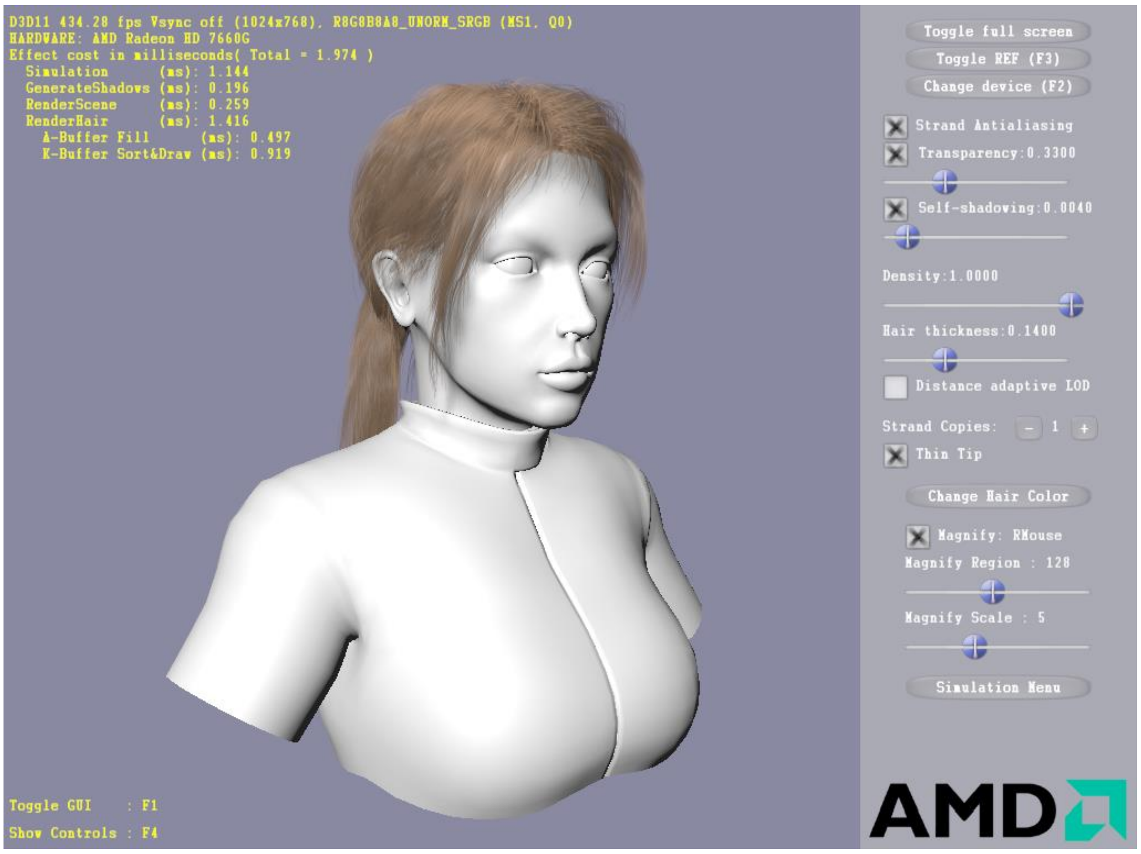
Detail LOD
Enable ✓
Start Distance 2.25
End Distance 0.75
Width 0.20
Density 1.00

Figure 4: Screenshot of NVIDIA HairWorks Viewer [NVIDIA 2014b]

At 26th June 2014 NVIDIA announced the release of their HairWorks tool chain for real-time hair and fur rendering [NVIDIA 2014c]. This technology was previously presented by [Kim 2014] at GTC 2014. NVIDIAs HairWorks is an enhancement of the NVIDIA Fermi Hair demo and was made ready for production. This technology was used for the game Call of Duty Ghosts. Here the fur of the wolves and the dog Riley was rendered and simulated with NVIDIA HairWorks. In The Witcher 3: Wild Hunt the technology of NVIDIA HairWorks was used for the hair of the main character Geralt and for other characters. Furthermore, the fur technology was applied to wolves and monsters of this game [Burnes 2014]. HairWorks supports a Maya and 3ds Max model pipeline. Additionally, NVIDIA has implemented the NVIDIA HairWorks Viewer tool for iterating and fine tuning. The technology is still based on the tessellation engine and includes view-space culling, back face culling, continuous distance LOD and continuous detail LOD. Continuous distance LOD adjusts based on the distance of the camera, hair density and thickness. Continuous detail LOD handles hair density and thickness during close up moments. The simulation was also improved to be more efficient. NVIDIA used therefore [Müller et al. 2012], which is based on [Kim et al. 2012]. For fur rendering they were able to render 500000 hairs out of 10000 guide hairs. Main bottleneck here was the rendering engine. Tessellation stages hull shader and domain shader had the highest execution time. Simulation took up only 10% to 20% of the overall time. Shader performance had to be lowered for flexibility. This adds the ability to pass additional attributes for more control over the hair style. The SDK is still in closed beta and requires licencing to get access to the source code. NVIDIA is working on the improvement of their technology and tools. They plan to enhance long hair dynamics, body collision and hair interaction. They also need to adapt to engine requirements like deferred shading support, motion blur, depth of field, ambient occlusion and shader caches.

2.3. AMD TressFX

Advanced Micro Devices (AMD) TressFX is a high-quality real-time hair rendering and physics system, which was first used for the game Tomb Raider in 2013. It was the first hair strand based hair rendering system used inside a video game. At FMX 2013 [Engel and Hodes 2013] presented about their integration of this technology inside the Tomb Raider and how they applied hair rendering and simulation to Lara Crofts hair. TressFX is based on [Yu et al. 2012]. Enhancements and improvements of this technology were later done by [Bilodeau and Han 2013] and released as TressFX11 v2.0 [AMD 2013]. In 2014 an article about hair rendering [Martin et al. 2014] and an article about hair simulation [Han 2014] were published in [Engel 2014].



```
D3D11 434.28 fps Vsync off (1024x768), R8G8B8A8_UNORM_SRGB (MS1, Q0)
HARDWARE: AMD Radeon HD 7660G
Effect cost in milliseconds( Total = 1.974 )
  Simulation      (ms): 1.144
  GenerateShadows (ms): 0.196
  RenderScene     (ms): 0.259
  RenderHair      (ms): 1.416
    A-Buffer Fill      (ms): 0.497
    K-Buffer Sort&Draw (ms): 0.919
```

[✓ Strand Antialiasing]
[✓ Transparency:0.3300]
[✓ Self-shadowing:0.0040]
Density:1.0000
Hair thickness:0.1400
Distance adaptive LOD
Strand Copies: 1
[✓ Thin Tip]
[✓ Magnify: RMouse]
Magnify Region : 128
Magnify Scale : 5

Figure 5: AMD TressFX11 v2.0 screenshot [AMD 2013]

With TressFX thousands of hair strands are simulated and rendered on the GPU. For physics simulation on the GPU Direct Compute is used. The capabilities of shader model 5.0 vertex shader is utilized for rendering. Lara Crofts hair had a spline count of about 21042 hair strands with 16 vertices per strand. These source hair strands were duplicated with an offset to achieve increased hair coverage. Flexibility is another key feature of TressFX, which allows different hair styles and different conditions for the hair. Hair strands are organized into primitive groups to support different configurations and therefore different simulation behaviour of hair parts. The hair strand vertex count has to be the same for all hair strands within a primitive group. Lara Crofts hair was separated into bangs, cap, fringe and ponytail. For each hair strand position, tangent, local/global quaternions, resting length and thickness were saved. The TressFX test model is organized into four primitive groups, which are called hair free, hair front long, hair pulled and hair tail. Hair tail has a vertex count of 14 vertices per hair strand and the other primitive groups have a vertex count of 11 vertices per hair strand. The strand count all together is 21809 hair strands.

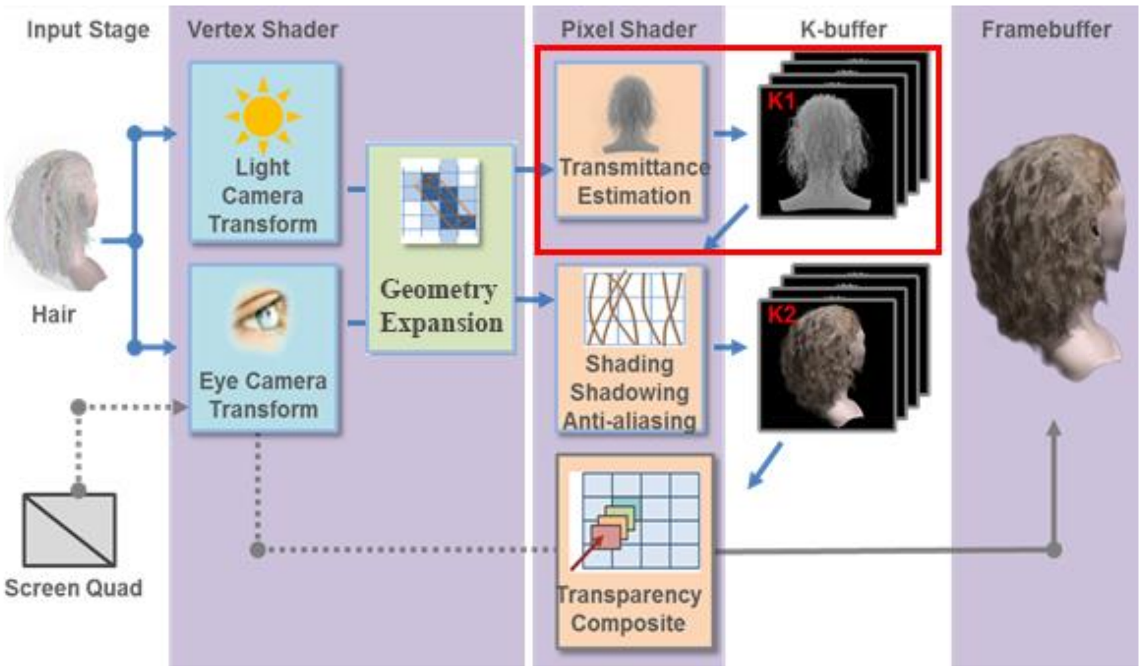


Figure 6: Rendering pipeline in Tomb Raider [Engel and Hodes 2013]

Figure 6 shows the render pipeline, which was used in Tomb Raider. The tessellation engine and the geometry shader was not utilized. Geometry expansion was done in the vertex shader. Here each hair segment is expanded into two triangles with a world-space direction vector, which is perpendicular to the hair. This direction vector is calculated with the cross product of tangent and view vector. A camera facing quad has at least a width of one pixel in screen space. Similar to 2.1 an empty vertex buffer and index buffer are used for the draw call to render the hair. The vertex ID is used to look up the right vertex data, which is saved in a buffer or a texture. The vertex count of the draw call is calculated dependent on the number of segments, which need to be rendered. This number is multiplied with 6 because each segment will be expanded to two triangles, which have a vertex count of 6. Output of the vertex shader is the position of the vertex, a tangent, the left hair edge and right hair edge in screen space, and texture coordinates. The left hair edge and right hair edge is needed for antialiasing calculations inside the pixel shader.

Lighting was done according to [Kajiya and Kay 1989] and [Marschner et al. 2003]. TressFX uses an approximation of [Marschner et al. 2003] when rendering two specular highlights. Additionally, a diffuse texture is used to support variation in hair colour. Crystal Dynamics had two rendering profiles for wet and dry hair in Tomb Raider.

Antialiasing was not done with SSAA or MSAA. An image based solution was used similar to geometric post-process anti-aliasing (GPAA) [Persson 2011]. Every hair strand is anti-aliased manually. The location of the hair fibre edges are used to evaluate each hair fragments distance with respect to these edges. The farther the pixel is inside the hair fibre, the more the coverage value is increased. Is the pixel more than 0.5 pixels inside the hair fibre, the coverage value is set to 1.0. Is the pixel on the hair fibre edge, coverage is 0.5. Coverage has the value of 0 when the pixel is more than half a pixel outside of the hair fibre.

For self-shadowing a simplified version of deep shadow maps [Lokovic and Veach 2000] was used. First, hair splines are rendered as lines to a shadow map. Afterwards depth in the shadow map is compared with the depth of the hair strand that is currently drawn. The distance between the hair strand that is currently drawn and the hair strand that is closest to the light determines how dark the shadow value of the current hair strand is. The bottom hair receives darker shadow values and top hair receives brighter shadow values. Each shadow value is stored in a per-pixel linked list (PPLL).

A PPLL was used for order independent transparency (OIT). The usage of a PPLL is based on [McKee 2011]. Transparency helps to simulate the presence of thin individual hair strands. For every pixel on the screen, which has one or more layers of hair, a linked list is generated containing each overlapping hair fragment. Two passes are executed. In the first pass, an A-buffer is filled with an unsorted linked list for each pixel on screen that contains hair fragments. Therefore, all strands are rendered and shaded in the pixel shader. In the second pass, the a-buffer of the previous path is traversed and the data is sorted in a k-buffer for the topmost hair pixels. 8 layers are sufficient enough for rendering. The influence of the 8th layer is barely over 1%. Sorting is performed using the depth stored in the linked list node. At the end the nearest k fragments are rendered in right order back to front. The remaining layer are just blended in out of order. This technique for transparency only works if hair does not take up the whole screen. Otherwise, it causes artefacts and the hair is not rendered correctly on screen.

First requirement for the simulation of TressFX was performance. More than 20000 hair strands needed to be simulated and the simulation should be possible within a game, where available resources for hair simulation are limited. This is the main reason because performance is more important than correct hair simulation. Other requirements were more artist based. The simulation should maintain a predefined hair style. Additionally, different conditions like wet and dry should be supported by the simulation. Hair should also be stable, respond to wind, gravity and external forces, and should allow collision handling with head and body. The simulation is based on [Han and Harada 2012].

Three constraints were used to achieve these requirements: global shape constraint (GSC), local shape constraint (LSC) and edge length constraint (ELC). GSC helps to preserve the initial hair shape. Initial positions of each hair strand vertex is saved and serves as the goal position of each particle. It is an easy and cheap solution and helps to maintain the hair style. As a result, detail of the hair simulation is lost. LSC is to simulate bending and twist effects. The last constraint is ELC. This is a hard constraint to simulate inextensible hair. ELC can be applied in parallel and does not converge for fast movement. For the case of fast movement, the constraint is switched to adhoc constraint, which updates only one vertex position at a time, starting from the root of the hair strand. The problem with the adhoc constraint is that it can add extra energy to the system. The adhoc constraint is only used when absolutely necessary.

Most of the simulation calculation is done on the GPU. The CPU is only needed at start up to load hair data and compute state values, which also can be precomputed. On the GPU the simulation loop is executed. First, gravity is applied and Verlet integration is executed. Afterwards, GSC, LSC, wind and ELC are applied. Collision is handled at the end of the loop. Shader code is separated into 5 shaders. The first shader is for gravity, integration and GSC. In the second shader LSC is applied. Wind application and length constraint is executed in the next shader. The fourth shader is responsible for extra length constraint for erratic movement to handle fast movement of the hair. The final shader does collision handling.

For simulation in Tomb Raider special cases needed to be handled. The simulation does not work when hair is placed upside down like in the sac swing part of Tomb Raider. At the first level Lara Croft is hanged on the ceiling upside down and needs to swing like a sack to release herself from the chains. An additional hair geometry had to be designed for this scene to give a realistic look. Other special cases were wet hair, weapon aiming and cinematics. Different hair settings were used for these situations. Blending between different hair settings was also possible. Settings were made for dry, mid wet, wet, weapon aiming, upside down, upside down sac swing and special cinematic clamp down.

The first version of TressFX only supported forward rendering. As a result, all hair fragments were shaded before they were sorted. Many hair segments were shaded that were not visible. At GDC 2014 [Thibieroz and Hillesland 2014] presented improvements, which were implemented into TressFX. One improvement was to use offline created vertex and index buffers to draw the hair indexed. Distance-based level of detail (LOD) was also an improvement. The input line segments have a random order. It is possible to render fewer lines with thicker fragments for lower level of detail. Another improvement to save performance was the use of deferred shading. With deferred shading hair fragments are shaded after the sort operation. This allows to use a level of detail for shading. Only the top most hair fragments have a huge influence on the final image quality. Tail fragments can be shaded with a simpler and faster shading operation. There is a very little quality difference compared to full shading, but shader LOD gives a much better performance. It was also presented why the tessellation engine was not used in their implementation. Thibieroz and Hillesland claimed that isoline tessellation is not cost effective because lines have to be expanded in the geometry shader, which is a major impact on performance. They also think that pure vertex shader solution is faster and curvature is barely a problem. However, they did not back up their claims with test results, which compares a tessellation based version with their version.

In conclusion, TressFX is fast enough to be used on next generation consoles like the PlayStation 4 and Xbox One. The deferred shading implementation gives a significant performance boost. There is still ongoing research to improve and expand the use of this technology for fur, grass and hair rendering. Especially, the quality of the simulation can be improved and combined in less shader stages.

3. Requirements

Since the hair rendering for this thesis is developed at the Research and Development department of the Institute of Animation at Filmakademie Baden-Württemberg there are multiple requirements and dependencies, which influence the implementation and the technology, which was used.

First, the hair has to be rendered in real-time. The target is to be able to render the virtual character with a frame rate of 60 FPS. The animation of the character needs to be calculated and additional to the hair, face geometry, eyes, eyelashes, eyebrows, the upper body and clothes needed to be rendered. All these assets share a frame time of about 16.6 milli seconds. Therefore, it is crucial to use as less time as possible for the rendering of the hair and at the same time keep or improve the visual quality.

High quality hair rendering consists of the generation of the hair, lighting, shadowing, handling of transparency and antialiasing. All these factors needed to be evaluated against the rendering times.

Level of detail was another important requirement. A target of the research project SARA is to find out if children and teenager with ASD or ADHD read the emotional states of the virtual character easier from a realistic character or an abstract character. Different level of detail settings allow to render fewer hair strands with a thicker width. Additionally, level of detail calculations should be evaluated for performance optimization and improvement of the visual quality of the rendered hair.

It is not only important to be able to render multiple strands of hair on the GPU. Another important requirement for this project was to be able to create multiple hair styles and to optimize the work flow for the creation of the hair rendering engine. The creation of the hair should be artist friendly. Generation of guide hairs should be possible with Maya, 3D Studio Max and Cinema 4D.

Another dependency of this project is that the virtual characters need to be implemented in the application framework Frapper [Helzle et al. 2014]. Shaders and the animation system were implemented into Frapper using mainly Cg shader. Frapper is based on the rendering engine Ogre3D [OGRE 2014], which supports in there released versions Cg, OpenGL2, DirectX 9 and DirectX 11. Ogre3D has also an OpenGL 3+ renderer. This renderer supports OpenGL shader above OpenGL 3, which also includes OpenGL 4 features. The problem of this renderer is that it was not officially released from the Ogre developers.

For the hair generation on the GPU, DirectX 11 or OpenGL 4 needed to be used in order to be able to utilize the tessellation functionality of modern graphics cards. Cg supports DirectX 11, which would have been the best solution given that it permits to reuse the old Cg and at the same time uses the features of the tessellation pipeline. On the other hand, Cg only supports OpenGL 4 for NVIDIA graphics hardware [NVIDIA 2014d]. Additionally, the OpenGL 3+ renderer of Ogre does not support Cg. Using OpenGL 4 with Cg in Ogre was therefore no option. Another argument against Cg is that NVIDIA stopped the support of Cg after the release of the Cg 3.1 Toolkit [NVIDIA 2014e]. For this reason, Cg is not a shader language to utilize future improvements of graphics cards.

The decision to use OpenGL 4 was also influenced by the need to implement other parts of the project including the non-photorealistic rendering algorithms in OpenGL.

After evaluation of the Ogre OpenGL 3+ renderer, which has proven to be a stable version, it was decided to implement the hair rendering algorithms in OpenGL 4. This meant that all previous written Cg shader for face, eye and cloth rendering had to be translated into OpenGL shading language (glsl).

4. OpenGL Tessellation Rendering Pipeline

Since the hair rendering is implemented in OpenGL 4 using its tessellation rendering stages, a brief overview of the OpenGL 4 tessellation pipeline is provided together with a more in-depth look at the tessellation stages. Khronos released the specification of OpenGL 4.5 at 11th August 2014. The core profile [Khronos Group 2014a] and quick-reference card [Khronos Group 2014b] gives in depth information about OpenGL 4.5. Another great overview of the OpenGL render pipeline gives [Khronos Group 2014c].

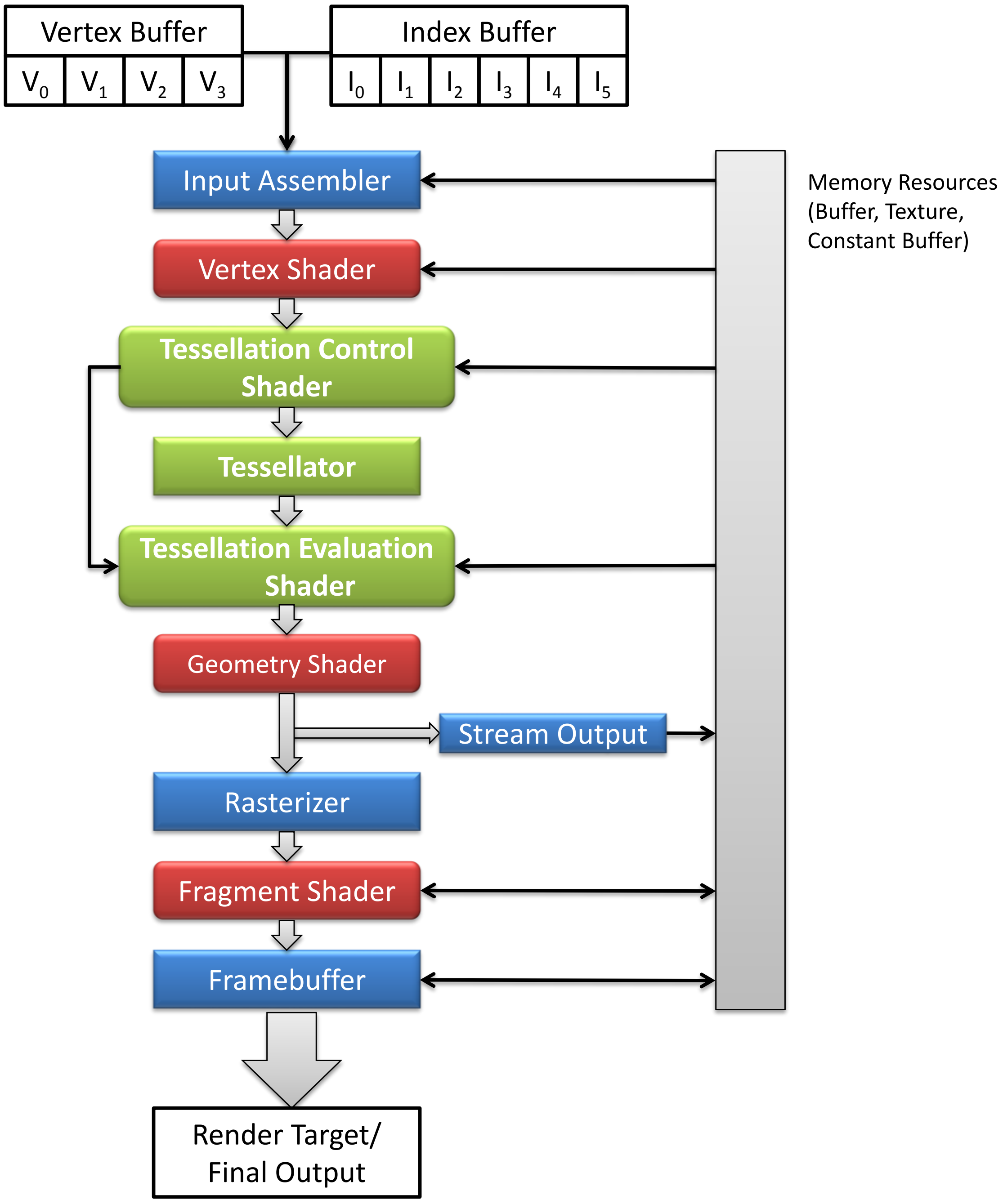

Vertex Buffer
V_0 V_1 V_2 V_3
Index Buffer
I_0 I_1 I_2 I_3 I_4 I_5
Input Assembler
Vertex Shader
Tessellation Control Shader
Tessellator
Tessellation Evaluation Shader
Geometry Shader
Stream Output
Rasterizer
Fragment Shader
Framebuffer
Render Target/ Final Output
Memory Resources (Buffer, Texture, Constant Buffer)

Figure 7: OpenGL tessellation pipeline overview

Figure 7 shows a simplified overview of the OpenGL 4 rendering pipeline. Data can be streamed in a vertex buffer and index buffer. The vertex buffer stores all specific vertex data, which includes the position of the vertex. Optional attributes can be added to the vertex buffer. Often normals, tangents, texture coordinates or blend weights are used as input. It is up to the programmer to decide, which input values need to be used. The index buffer helps to reduce the size of the vertex buffer because no duplicates have to be saved in the vertex buffer. Its use is optional as objects can be drawn with and without index buffer.

The programmable shader stages are vertex shader, tessellation control shader (TCS), tessellation evaluation shader (TES), geometry shader and fragment shader. TCS, TES and geometry shader are optional. TCS, tessellator and TES form the tessellation shader stage. All shader stages have access to memory resources, which consist of textures, buffers and constant buffers.

4.1. Vertex Shader

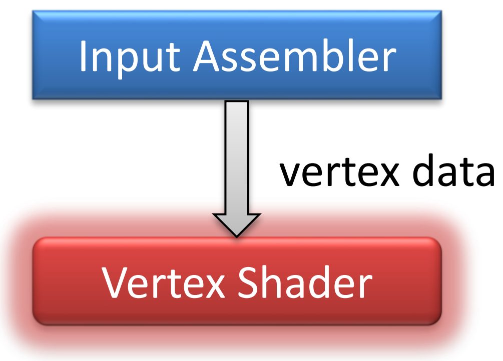


Figure 8: Vertex shader

The vertex shader is the first programmable shader stage of the OpenGL tessellation pipeline. As input the vertex shader gets a vertex stream. The vertex shader is executed once per input vertex of the vertex stream. Calculations and transformation can be performed per vertex. Additional data can be passed through to the next programmable shader stage. If tessellation is enabled, data will be passed through to the TCS. Otherwise, data will be passed through to the pixel shader. In the vertex shader geometric transformation has to be performed if the tessellation stage is disabled. The resultant vertices of the input shader are assembled afterwards into primitives. Additional fixed inputs that can be accessed from the vertex shader are `gl_VertexID` and `gl_InstanceID`. `gl_VertexID` is the index of the current vertex and `gl_InstanceID` is the index of the current instance. OpenGL also has predefined outputs for the vertex shader, which is defined in an interface block without an instance name. The most important one is `gl_Position`, which is the output vertex data. This variable has to be used for the output data. `gl_PointSize` is only used for

```
out gl_PerVertex
{
        vec4 gl_Position;
        float gl_PointSize;
        float gl_ClipDistance[];
}
```

Figure 9: Vertex shader predefined output

point primitives. It describes pixel width and height of the point. The last predefined output is the array `gl_ClipDistance`. Here the distance of the vertex to each clip plane can be defined.

4.2. Tessellation Control Shader

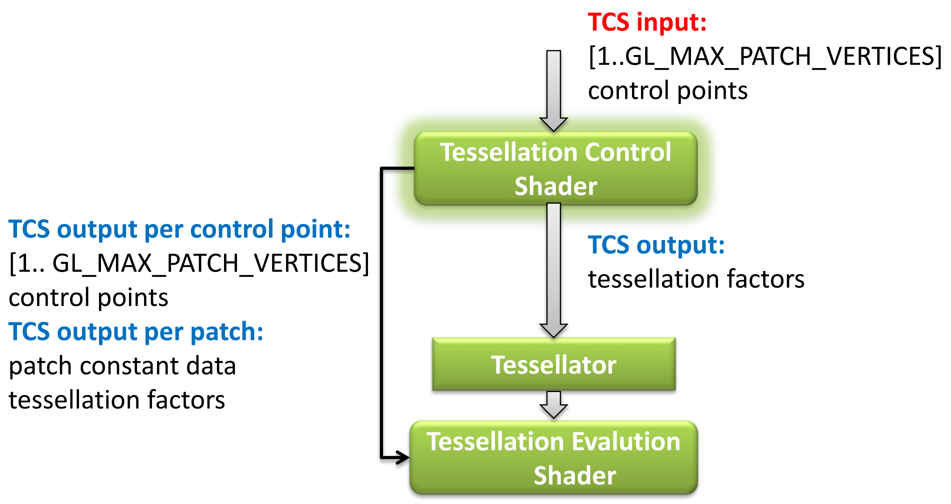


Figure 10: Tessellation control shader

First, it needs to be defined how many control points will be used per primitive. The maximum number of output control points is hardware dependent, but never smaller than 32. Figure 11 shows the definition inside the TCS, where `patch_size` is the number of defined control points.

```
layout(vertices = patch_size) out;
```

Figure 11: Output patch size definition

The TCS is executed once per tessellation primitive. Three different primitive types can be handled by the tessellation engine: quads, triangles and isolines. Dependent on the primitive type tessellation factors need to be calculated. These are set in `gl_TessLevelOuter[4]` and `gl_TessLevelInner[2]`. For quads all tessellation levels are used. Triangles only need the first three outer tessellation levels and the first inner tessellation level. For isolines only the first two outer tessellation levels need to be set. Tessellation values are between 0.0 and 64.0. If all tessellation values are set to 0.0, the primitive is not rendered and all shader stages after the TCS are not called for the current primitive.

```
out gl_PerVertex
{
        vec4 gl_Position;
        float gl_PointSize;
        float gl_ClipDistance[];
} gl_out[];
```

Figure 12: TES predefined output

Fixed input for TCS is `gl_PatchVerticesIn`, `gl_PrimitiveID` and `gl_InvocationID`. `gl_PatchVerticesIn` gives the number of vertices in the input patch. `gl_PrimitiveID` is the index of the current patch and `gl_InvocationID` is the index of TCS invocations. The tessellation stage is also used to calculate per patch and per vertex attributes, which are passed through to the TES. Per vertex attributes have to be outputted in an array, which has the same size as the predefined number of output control points. Predefined output is the same as in the vertex shader. It is defined as an array for every control point. It is not necessary to set any of the predefined output data.

4.3. Tessellator

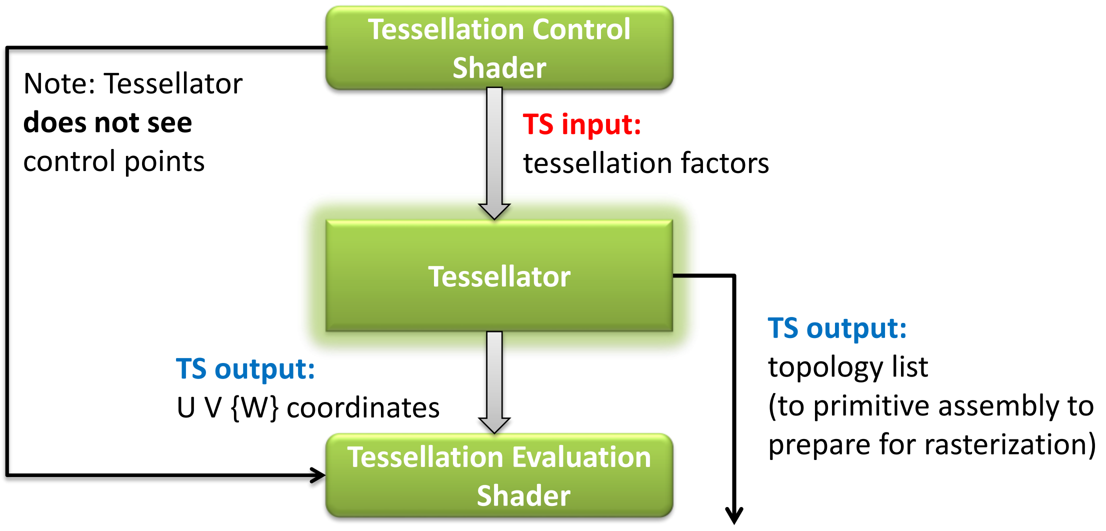

Tessellation Control Shader
Note: Tessellator **does not see** control points
TS input: tessellation factors
Tessellator
TS output: U V {W} coordinates
TS output: topology list (to primitive assembly to prepare for rasterization)
Tessellation Evaluation Shader

Figure 13: Tessellator

The tessellator, which is also called tessellation primitive generator, is a fixed-function stage. Dependent on the tessellation primitive, spacing, primitive order and the defined tessellation factors, the tessellator generates UVW coordinates values per tessellated vertex and passes these values to the TES. Barycentric coordinates are calculated for triangles. For quads and isolines UV coordinates will be generated by the tessellator.

Spacing can be defined as `equal_spacing`, `fractional_even_spacing` and `fractional_odd_spacing`. Tessellation levels are defined in float values. `equal_spacing` rounds up each float value to the nearest higher integer. Each edge is divided into *n* segments of the same size. Range is from one to the maximum tessellation value. `fractional_even_spacing` has range from two to maximum tessellation value. The tessellation value is rounded up to the nearest even integer. Segment sizes vary in this spacing scheme. It starts at level two with one subdivision. This subdivision is represented with the original vertices of an edge and one new generated vertex. With a tessellation value between 2.0 and 3.0, two new generated points move from the first tessellated vertex to one of the original vertices. This scheme is used to support a smooth transition between tessellation levels. It can be used for distance dependent and view-space dependent tessellation.

`fractional_odd_spacing` also generates non-uniform segment sizes. Its range is from one to maximum tessellation level minus one and rounds up the tessellation value to the nearest odd integer values. Only one segment is drawn when the tessellation factor is between 0.0 and 1.0. Between tessellation value 1.0 and 3.0, two new vertices are generated at the position of the original vertices, which move into the middle of the line. `fractional_even_spacing` and `fractional_odd_spacing` is not drawn when the tessellation factor is smaller than 0.0. The primitive order can be changed between clockwise and counter clockwise.

4.4. Tessellation Evaluation Shader

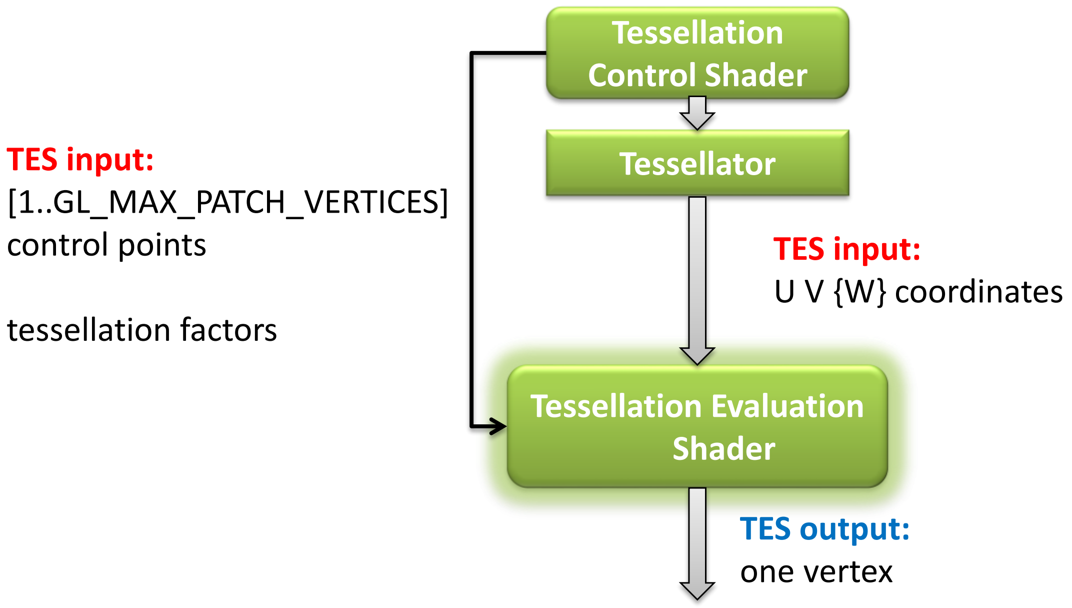

Tessellation Control Shader
Tessellator
TES input:
[1..GL_MAX_PATCH_VERTICES] control points
tessellation factors
TES input:
U V {W} coordinates
Tessellation Evaluation Shader
TES output:
one vertex

Figure 14: Tessellation evaluation shader

The TES is used to calculate the final vertex position of the generated vertex. The TES gets as input UV{W} coordinates from the tessellator. Additionally, tessellation factors, per patch input data and per control point data are provided from the TCS for the TES.

```
layout(param1, param2, ...) in;
```

Figure 15: Tessellation options definition

In the TES tessellation options for the tessellater can be defined. Figure 15 shows the line of code, which has to be inserted before the main function of the TES shader. Parameters can be patch type (`isolines`, `triangles`, `quads`), spacing (`equal_spacing`, `fractional_even_spacing`, `fractional_odd_spacing`) or primitive ordering (`cw, ccw`).

Built-in inputs are `gl_TessCoord`, `gl_PatchVerticesIn` and `gl_PrimitiveID`. UV{W} can be accessed with `gl_TessCoord`. `gl_PatchVerticesIn` is the vertex count of the patch and `gl_PrimitiveID` is the index of the current patch. Tessellation factors can be accessed with `gl_TessLevelOuter` and `gl_TessLevelInner`. The built-in per vertex input from the TCS can be accessed with `gl_in`. The struct is except of `gl_in` the same as in Figure 12. The built in per vertex output is the same as for the vertex shader.

4.5. Geometry Shader

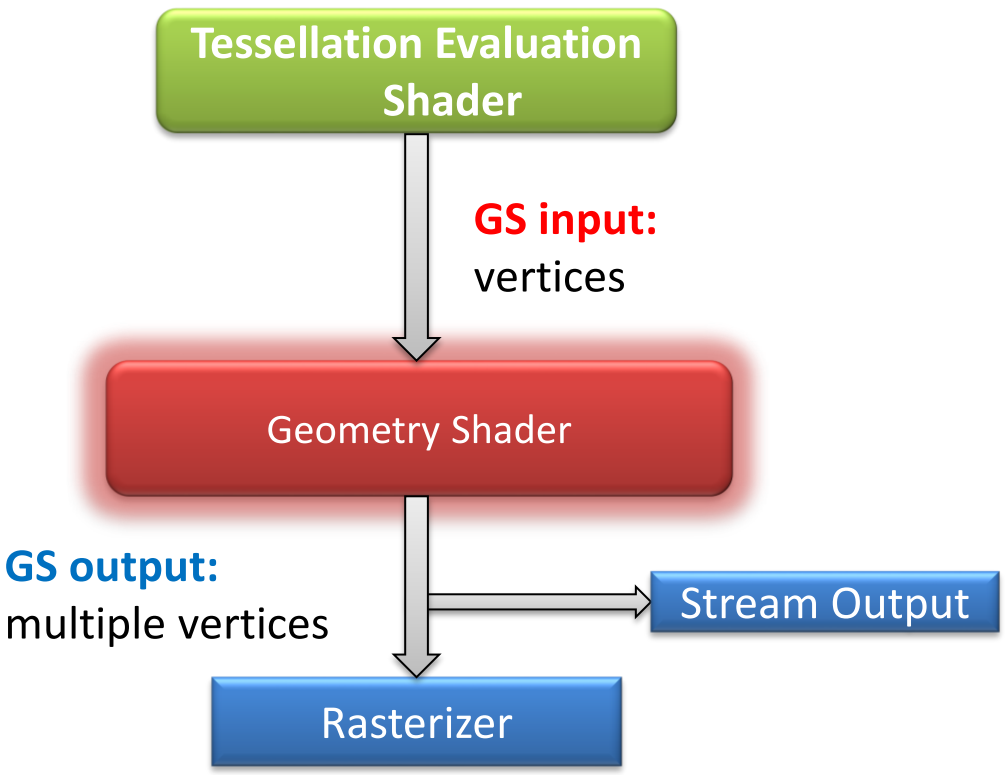


Figure 16: Geometry shader

The geometry shader is executed either after the vertex shader or after the TES if tessellation is activated. It uses a single primitive as input and outputs zero or more primitives. Input and output primitives can be of different types. The geometry shader is optimized for small geometry expansions. Theoretically, the geometry shader can be used for tessellation, but this would not be very efficient. The main areas the geometry shader is useful are layered rendering, transform feedback and transformation of primitive types. With layered rendering it is possible to render one primitive to multiple images or render targets. In transform feedback the captured primitive from the vertex processing step can be saved to buffer. Vertex processing steps can include vertex shader and the tessellation stage. Transformation of primitives is a general use case for the geometry shader. One example for that is the expansion of lines to quads.

```
// geometry shader input
layout(input_primitive) in;

// geometry shader output
layout(output_primitive, max_vertices = vert_count) out;
```

Figure 17: Geometry shader input and output declaration

Figure 17 shows how the input and output of the geometry shader is defined. For the input of the geometry shader only the input primitive type has to be defined at `input_primitive`. The available primitive types are `points`, `lines` and `triangles`. For the geometry output `output_primitive` and `vert_count` need to be set. Output primitives can be `points`, `line_strip` or `triangle_strip`. Additionally, the maximum number of vertices, which can be generated by the vertex shader, needs to be defined. This number of vertices is a hardware limited factor defined by `MAX_GEOMETRY_OUTPUT_VERTICES`, which has a minimum value of 256.

```
layout(invocations = num_instances) in;
```

Figure 18: Geometry shader instancing

OpenGL 4 has a new instancing feature available. The geometry shader can be executed multiple times per input primitive. Figure 18 shows the declaration of geometry instancing. With `num_instances` it needs to be defined how many times an input primitive will be executed. The maximum number is defined with `MAX_GEOMETRY_SHADER_INVOCATIONS` and is at least 32.

Another feature of the geometry shader is layered rendering. Specific primitives can be send to different layers of a layered frame buffer. This functionality can be used for the creation of shadow maps.

Built-in input is `gl_PrimitiveIDIn` and `gl_InvocationID`. `gl_PrimitiveIDIn` is the ID of the input primitive while `gl_InvocationID` is the current instance ID. `gl_InvocationID` can be different to `gl_PrimitiveIDIn` when instancing is activated. The built-in output is the same interface as for the vertex shader and TES. Another built-in output is `gl_PrimitiveID`. This output will be passed to the fragment shader and can be freely defined. For layered rendering two additional built-in output values can be set. `gl_Layer` defines the output layer and `gl_ViewportIndex` sets the output view port.

4.6. Fragment Shader

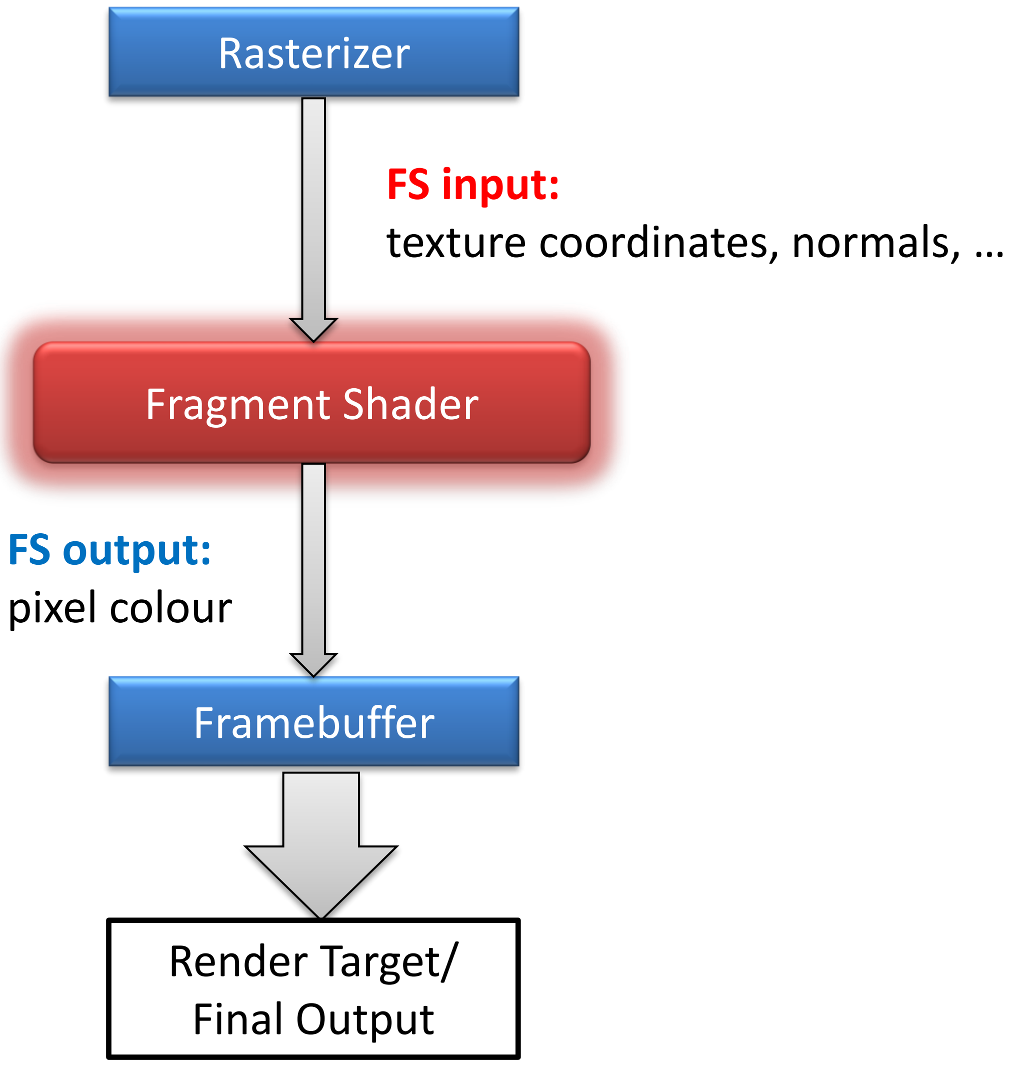


Figure 19: Fragment shader

The fragment shader gets as input fragments, which are the result values of the rasterizer. The fragment size is related to a pixel area. Multiple fragments are possible per pixel. The fragment shader is executed once per fragment. Main purpose of the fragment shader are lighting calculations, texturing and screen space calculations. The fragment shader calculates the pixel colour values of the rendered image, which are in the end saved to the frame buffer.

Built-in inputs are the 4D vector `gl_FragCoord`, the boolean value `gl_FrontFacing` and 2D vector `gl_PointCoord`. The location of a fragment in screen space is described with `gl_FragCoord`. The x value is the x position on the screen, the y value is the y position, the z value is the depth and the w value is `1/W_clip`, where `W_clip` is the interpolated w component of the clip-space vertex. If the primitive is from a front face or from a back face is located in `gl_FrontFacing`. `gl_PointCoord` describes the 2D location within in a point primitive. The only point primitive in OpenGL is `GL_POINTS`. Points have square or circle form. The coordinates are in a range from 0 to 1, where (0, 0) is the upper right corner.

OpenGL 4.0 specific inputs are sample attributes, the array `gl_ClipDistance`, and `gl_PrimitiveID`. When sample attributes are used the shader is forced to evaluate per-sample. The use of samples should be avoided and only used when absolutely needed. Sample attributes are `gl_SampleID`, `gl_SamplePosition` and `gl_SampleMaskIn`. `gl_SampleID` is the ID of the current sample. The 2D vector `gl_SamplePosition` supplies location of the current sample within a pixel area. The array `gl_SampleMaskIn` defines the sample mask for multi-sampled rendering and the array is as long as the supported sample count of OpenGL. `gl_ClipDistance` provides the interpolated clipping space values. The ID of the current primitive is stored in `gl_PrimitiveID`. If the geometry shader is enabled, `gl_PrimitiveID` is the value the geometry shader provided.

OpenGL 4.3 expands the fragment shader built-in input with the layer number `gl_Layer` and the viewport number `gl_ViewportIndex`.

```
layout(location = 3) out vec4 diffuseColor;
```

Figure 20: In-shader specification

Built-in outputs `gl_FragDepth`, `gl_SampleMask` and fragment colours. The fragment depth is stored in `gl_FragDepth`. If fragment depth is not set, the z value of `gl_FragCoord` is saved instead. The integer array `gl_SampleMask` defines sample masks for the fragment shader when performing multisampled rendering. Output buffers are the most important output of the fragment shader. The output is a series of colours, which are called fragment colours and stored as a framebuffer. A framebuffer is a collection of buffers and can be used for rendering. There are three ways to assign fragment buffers. The first possibility to declare a buffer as an in-shader specification with the layout modifier shown in Figure 20. An alternative is a pre-link specification. The OpenGL function `glBindFragDataLocation` needs to be called with the arguments name of the program, the colour number to assign and the fragment shader name. The last possibility is to use auto assignment. However, auto assignment is not recommended because the assignment is arbitrary.

4.7. Tessellation Primitive Isolines

Isolines are the tessellation primitive, which can be used best for hair rendering. Because of this reason, this section describes how isolines are used within the tessellation stage. Isolines have two parameters. The tessellation factor defines how many copies of the line are generated and the detail factor defines in how many parts a single line segment is separated. The tessellation factor is set in `gl_TessLevelOuter[0]` and the detail factor is set in `gl_TessLevelOuter[1]`. The maximum number of generated lines and line subdivision is 64. Different spacing values have no influence on the tessellation factor. The detail factor is influenced by spacing settings.

The first example in Figure 21 shows isolines generation with `equal_spacing` setting. Detail tessellation factor 1.0 and detail factor 1.0 display the original input line segment without any subdivisions. Is the detail factor set to 2.0, two line segments are generated out of the input line segment. The tessellation factor defines how many copies of the line are rendered. In this example three line copies were generated.

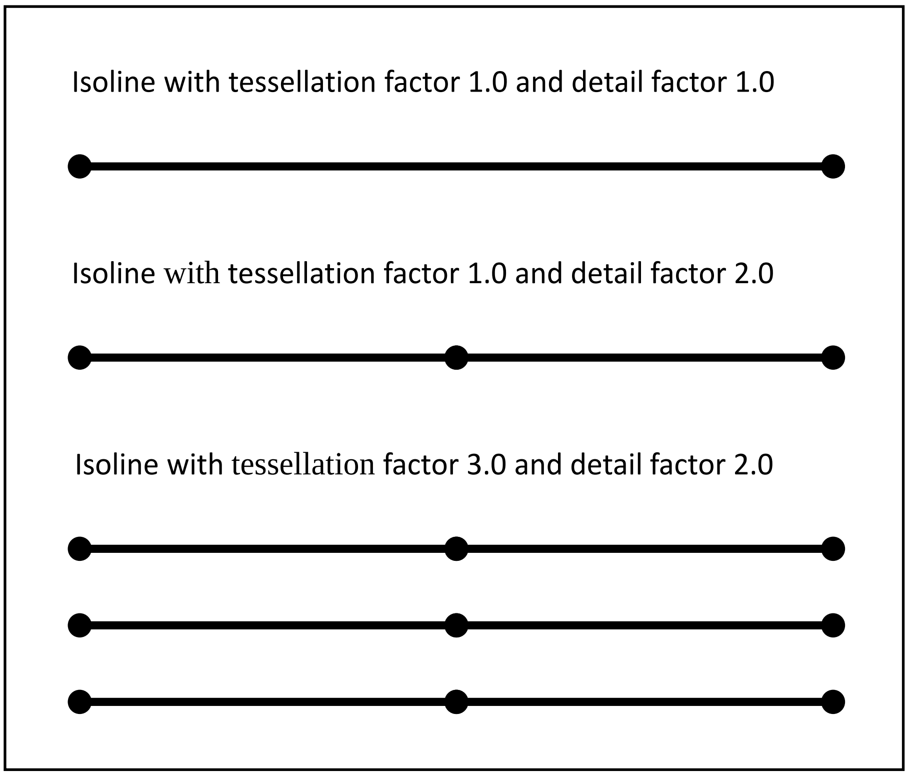

Isoline with tessellation factor 1.0 and detail factor 1.0
Isoline with tessellation factor 1.0 and detail factor 2.0
Isoline with tessellation factor 3.0 and detail factor 2.0

Figure 21: Isoline example `equal_spacing`

Figure 22 demonstrates how different detail factor settings influence the position of the generated vertices inside the line segment with the spacing setting `fractional_even_spacing`. Note that the generated line has at least one subdivision. With `fractional_even_spacing` it is not possible to render the original line without subdivision. In this example, it is shown how the new generated vertices move from the middle to their final position with a detail factor between 2.0 and 4.0. Is the detail tessellation level greater than 4.0, four new vertices are generated at the position of the two previous generated vertices. Two of these new generated vertices move left to their initial position and the other two move right to their previous position. At a detail factor 6.0 the vertices are arrived at their final position. Here all line segments have the same size.

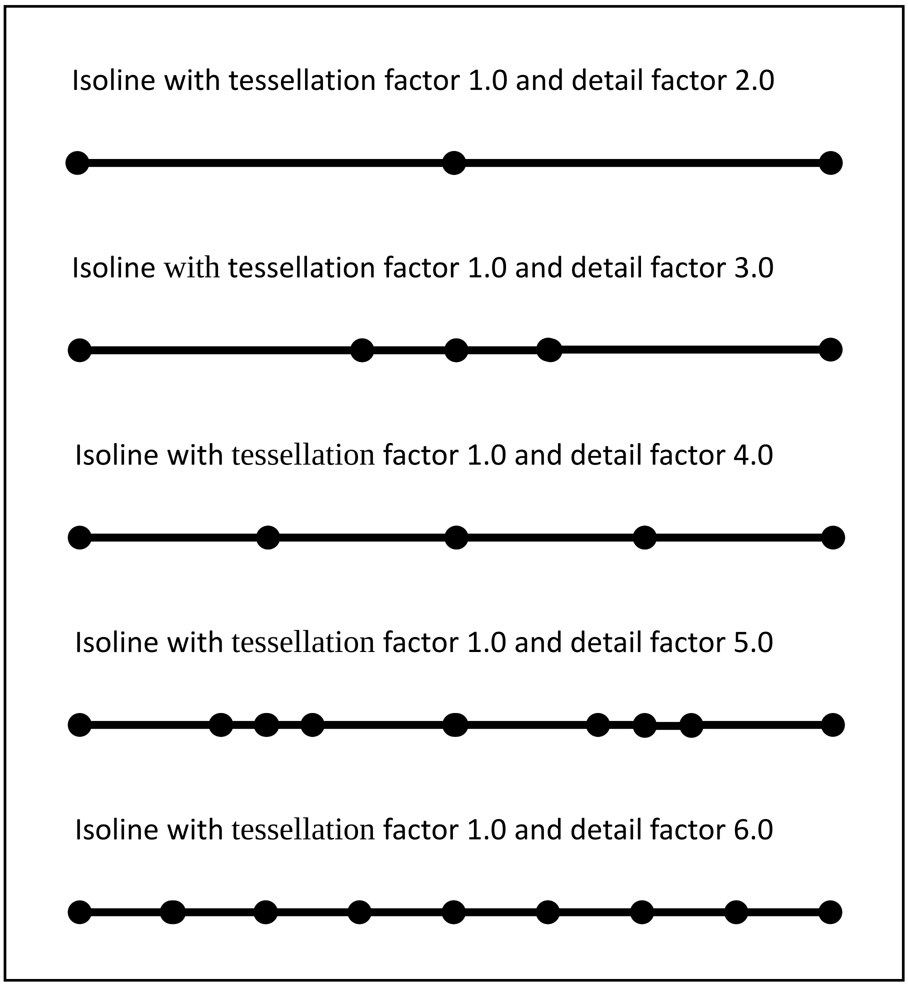

Isoline with tessellation factor 1.0 and detail factor 2.0
Isoline with tessellation factor 1.0 and detail factor 3.0
Isoline with tessellation factor 1.0 and detail factor 4.0
Isoline with tessellation factor 1.0 and detail factor 5.0
Isoline with tessellation factor 1.0 and detail factor 6.0

Figure 22: Isoline example `fractional_even_spacing`

The last spacing technique is `fractional_odd_spacing`. Here the input line can be displayed without subdivision. It is shown how two new vertices are generated and change their position between the detail factor 1.0 and 3.0. Is the detail factor greater than 3.0, two new vertices are generated at the position of the last two generated vertices. The new generated vertices as well as the previous two generated vertices move in opposite direction until detail factor 5.0 is reached, where all generated sub segments of the line have the same size.

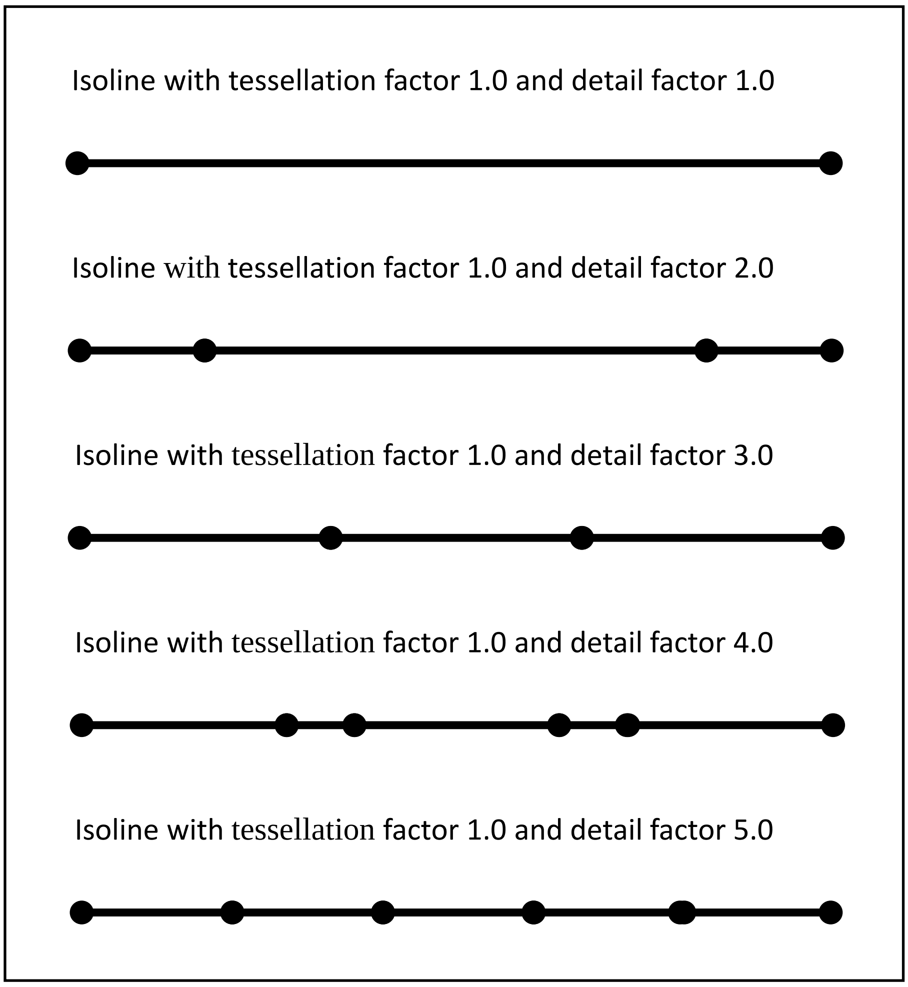

Isoline with tessellation factor 1.0 and detail factor 1.0
Isoline with tessellation factor 1.0 and detail factor 2.0
Isoline with tessellation factor 1.0 and detail factor 3.0
Isoline with tessellation factor 1.0 and detail factor 4.0
Isoline with tessellation factor 1.0 and detail factor 5.0

Figure 23: Isoline example `fractional_odd_spacing`

5. Implementation

In this section all implemented features for the hair rendering system are described. Main focus for this work was to implement a realistic looking hair rendering system with a huge number of hairs and at the same time provide a level of detail system to control the geometric detail as well as the needed processing power of the graphics card. Hair simulation is not a focus of this work and has therefore not been implemented. But the possibility for future implementation should still be provided.

The implementation of the hair rendering system is mainly based on Tariq’s work described in section 2.1. Tariq’s implementation was chosen as a basis over AMD TressFX, which was described in section 2.3, because Tariq’s work showed the better results for hair rendering, uses a more realistic hair simulation, has a smaller amount of guide hairs and utilizes the tessellation pipeline. Especially, the tessellation pipeline allows more flexibility and control over the tessellated hairs for level of detail purposes. The number of generated hairs, the subdivision of each hair segment as well as the width of the hair can be manipulated per TCS call, which is called once per hair segment of the guide hair. Tariq also implemented two different hair interpolation techniques, which allow to show different hair styles. Additionally, there is support of curly hair, random deviations and thinning. Overall, Tariq’s implementation allows more flexibility over the final hair style with less guide hairs, which allows lower memory consumption and less data has to be transferred from the CPU to the GPU. AMD TressFX on the other side is more performance optimized, which would free up calculation power for other algorithms of our character pipeline. However, the main problem with AMD TressFX is that artefacts appear when the hair style takes up more than the whole screen. Because our characters are rendered at a close up view, this is a visual bug, which is unthinkable for our implementation. Therefore the only way to use AMD TressFX is without the linked list ordering for hair geometry, which is the cause of the visual artefacts.

Another reason to use an implementation that utilizes the tessellation pipeline is because it also can be used to render face and cloth geometry more efficiently and with less memory consumption. It is possible to implement a view-dependent level of detail, which could be useful for the future of our character rendering pipeline. The tessellation pipeline would also allow to decide how much geometry detail is generated per frame. Therefore a version of our characters with less geometric detail would be possible. We would also have the possibility to have a continuous transition between low poly geometry and high detail geometry.

In the following subsections it is described how input data for hair rendering is represented and used within Frapper. Afterwards, the implementation of hair strand interpolations techniques single strand, multi strand and the combination of both are explained. In the next subsection it is evaluated how different hair guide sizes can be used with single strand and multi strand interpolation, where multi strand interpolation proves to be more challenging to get right. In the following subsections random deviations, curly hair and thinning are explained. At the end of the implementation paragraph, level of detail techniques as well as the used hair shading are shown.

5.1. Input Data

As input data of the hair guide hairs and a scalp mesh is needed. Guide hairs are a small number of hairs, which define the form and density of the hair style. These guide hairs can also be used for hair simulation. Each guide hair is saved as a separate submesh within the Ogre mesh file. A guide hair is a `line_strip`, which includes vertex buffer of all guide hair vertices. These vertices define the form of the hair. First vertex is the root vertex and the last vertex of the `line_strip` is the tip vertex of the hair. Two neighbouring vertices build a hair segment.

The scalp mesh is very important for multi strand interpolation to be able to pick the neighbouring guide hairs. The scalp mesh is a mesh, which describes the scalp of the character. Each vertex of the scalp mesh represents a root vertex of a hair guide. Best practice is to place the root vertex of a guide hair at the same position as a vertex of the scalp mesh. If that is not the case a distance variable was added to the system, which allows a small distance between root vertex of the hair and scalp mesh vertex. With that it is possible to use input data even when scalp mesh vertices and root vertices of guide hairs are not exactly the same, which can simplify the work of the hair artist.

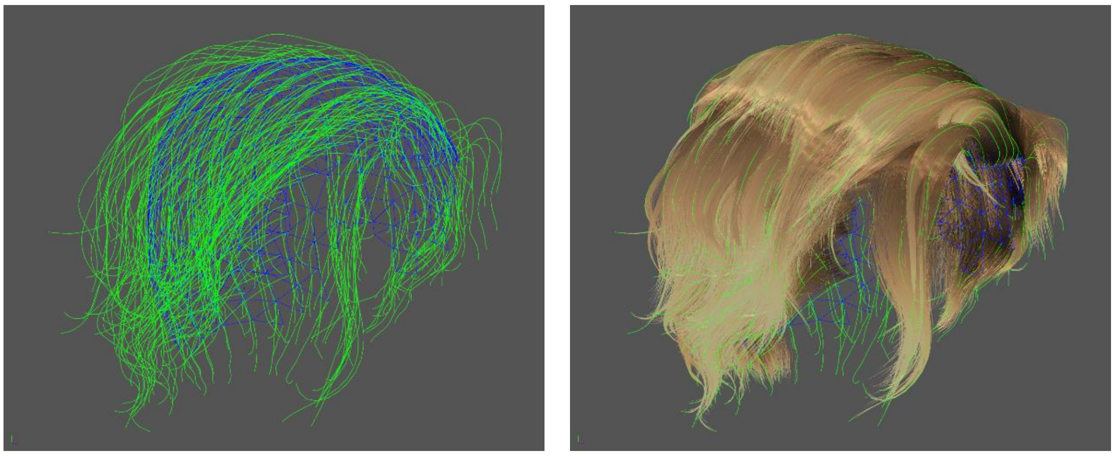


Figure 24: Guide hairs and scalp mesh (left), guide hairs and scalp mesh with rendered hair (right)

These guide hairs and the scalp mesh can be created with Maxon Cinema 4D, Autodesk Maya or Autodesk 3DS Max and exported with the Ogre mesh exporter. For our character Sara the hair style was created by Kai Götz within Cinema4D. First, a scalp mesh needs to be modelled. Afterwards, all faces of the scalp mesh need to be selected to generate hair splines at the position of the scalp mesh vertices. Thereafter, the form of the splines can be modified. For the export all guide hairs need to be saved in a separate mesh and the amount of guide hair segments per guide hair need to be defined. The lower the number of hair guide segments, the faster will be the rendering of the guide hairs. However, the geometry detail and control over the final form of the hair will be less. The data has to be exported first in Cinema 4D as an FBX file. This file needs to be loaded into Autodesk Maya, where hair and scalp mesh can be exported with the Maya Ogre exporter. Description about how to design and export hair styles have been supported by Kai Götz [Götz 2014b, 2014a].

This generated guide hair is read in at start up. For every vertex of the scalp mesh a corresponding guide hair is searched. When the guide hair is found, all vertices of the guide hair are saved within a guide hair position texture, which can be accessed at run-time by the TCS. Additional information that need to be saved to the guide hair vertices are the size of the guide hair as well as the distance to the tip of the current hair guide vertex. This additional data has to be saved to be able to support different hair sizes. In the end, the index buffer of the scalp mesh can be used to select the right guide hairs for multi strand interpolation.

5.2. Single Strand Interpolation

The idea of single strand interpolation is to use a single hair guide as input for the interpolation of generated hair strands. Two different techniques were tried out for single strand interpolation.

The first implementation is based on the Archimedean spiral algorithm [Rutter 2000]. For the implementation the parametric equation was used, where:

$$x = a\,\varphi \cos(\varphi), \qquad y = a\,\varphi \sin(\varphi) \qquad (\varphi \geq 0)$$

For the implementation the glsl code in Figure 25 was used inside the TES for the position calculation of the generated hair strand vertices.

```
// Parameters for the wisp shape
float r1 = g_rootRadius + g_tipRadius * gl_TessCoord.x;
float f1 = gl_TessCoord.y * 20 + 1;

// Order generated hair strands as Archimedean spiral
vec4 finalPosition = vec4( position.x + f1 * cos(f1) * r1,
                           position.y,
                           position.z + f1 * sin(f1) * r1, 1.0);
```

Figure 25: Archimedean spiral implementation glsl

With `g_rootRadius` and `g_tipRadius` can be controlled how hair strands are tapered in direction of the hair tip. `gl_TessCoord.x` gives the position within the hair segment while `gl_TessCoord.y` defines, which generated hair strand is called for the current invocation of the TES. The calculated values are used to offset the previous position of the hair in x and z direction. Results are shown in Figure 26. For the debug view on the left this implementation gives nice results. However with shading the pattern of the spiral is visible. Additionally, offset in x and z direction is not the perfect solution especially for hair strands at the side of the head.

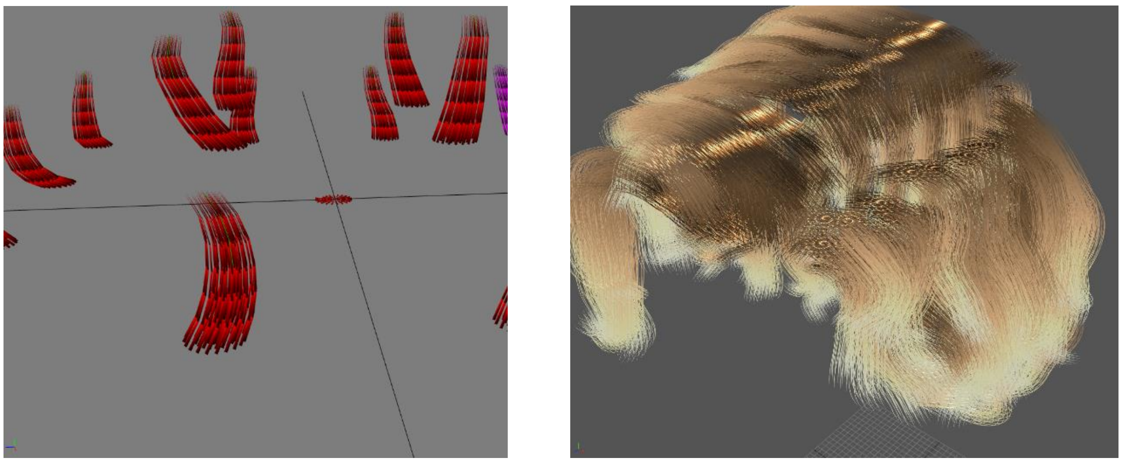
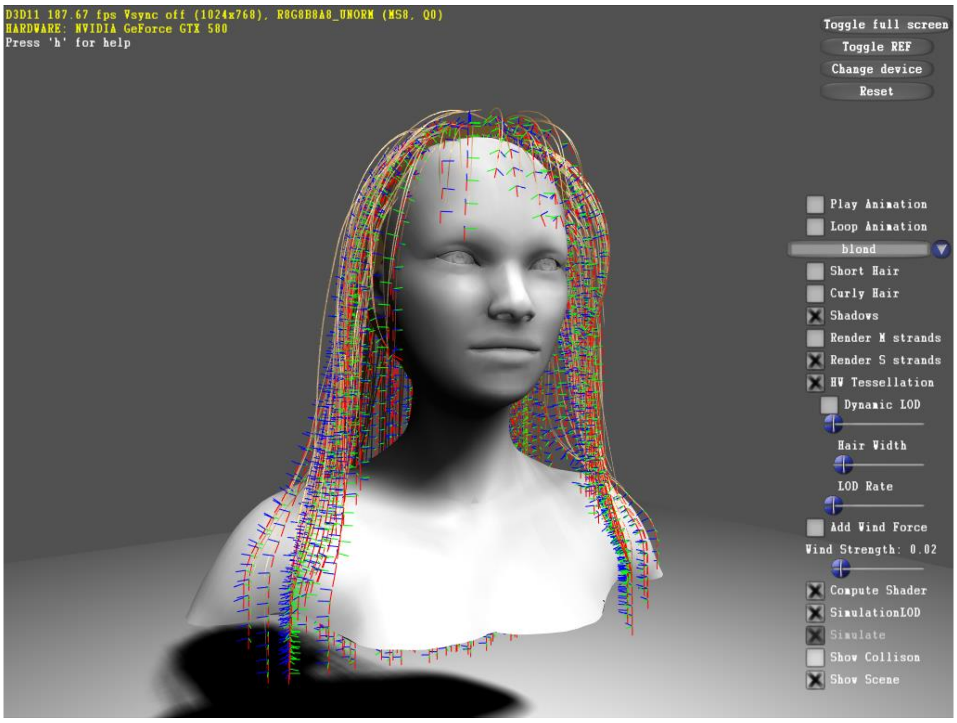


Figure 26: Results Archimedean spiral



```
D3D11 187.67 fps Vsync off (1024x768), R8G8B8A8_UNORM (MS8, Q0)
HARDWARE: NVIDIA GeForce GTX 580
Press 'h' for help
```

Figure 27: Rendering of coordinate frames for Fermi Hair Demo [NVIDIA 2010b]

Another approach that was tried out are random circular coordinates. Idea is to offset the generated hair with random values along their coordinate frames. One coordinate frame are three vectors, which define the plane the hair is offset at each vertex of the guide strand. Figure 27 illustrates how this three vectors, which are perpendicular to each other, look like for every vertex of the guide hair strand. One vector is calculated according to the tangent along the guide hair segment. This vector is used to calculate the other two vectors.

Random circular coordinates are calculated with Box-Muller Transformation, which guarantees a normal distribution for

$$X_1 = \sqrt{-2\log(U_1)}\cos(2\pi U_2)$$

$$X_2 = \sqrt{-2\log(U_1)}\sin(2\pi U_2)$$

when U_1 and U_2 are independently distributed within the range from 0.0 to 1.0 [Gentle 2003]. The offset result is saved within a texture and accessed in the TES at rendering time.

```
//create the new position for the hair clump vertex
float radius =      g_clumpWidth * ( g_rootRadius*(1-lengthToRoot) +
                    g_tipRadius*lengthToRoot );
vec4 finalPosition;
finalPosition.xyz =
       position.xyz +
       yAxisCF * clumpCoordinates.x*radius +
       zAxisCF * clumpCoordinates.y*radius;
```

Figure 28: Random circular coordinates glsl implementation

The glsl code to use the random circular coordinates is shown in Figure 28. Variables, which influence the form of the generated hairs are `g_clumpWidth`, `g_rootRadius` and `g_tipRadius`. With `g_climpWidth`, the overall width of the clumped hair is described. The maximum radius of the root and the maximum tip radius can be set with `g_rootRadius` and `g_tipRadius`.

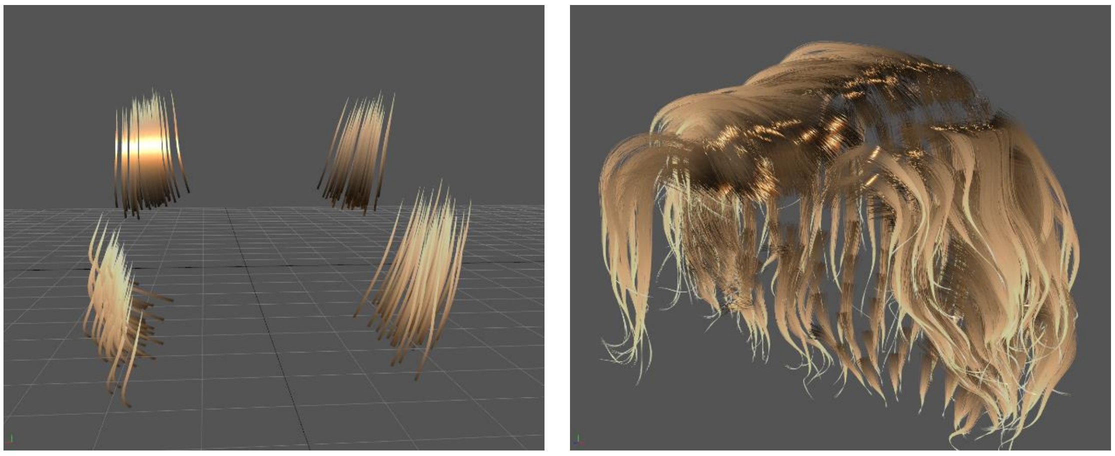


Figure 29: Result random circular coordinates

Result is a random distribution pattern, where no form is visible with shading. This single strand interpolation technique is good to render clump based hair. It is easy to implement for different hair sizes because interpolation pattern is only dependent on one hair strand and one size. Another advantage of single strand rendering is its performance. With single strand rendering less texture fetches and less calculations need to be performed compared to multi strand rendering. However, single strand rendering alone does not give good enough visual results to render a hair style. It needs to be combined with another hair interpolation technique for better results.

5.3. Multi Strand Interpolation

Multi strand interpolation uses three guide hairs for interpolation. Each TCS invocation uses three vertices for input. These can be the three root vertices of the guide hairs or three other vertices with the same distance to the root. These three vertices build together a triangle on which a new generated vertex is placed dependent on random generated barycentric coordinates.

To make this operation clearer a simple example is used with three hair guides, which all have a vertex count of three and therefore two segments. For these three guide hairs the TCS is called three times to read in the right vertex data on which barycentric interpolation is performed. One call is for the root vertices, one call for the vertices in the middle and another call for the tip vertices. After the vertices are read in the TCS, the hair segment is tessellated dependent on tessellation and detail factor. In the TES the calculation of the final vertex position for multi strand rendering takes place. For the simplest case with tessellation factor one and detail tessellation factor one the TES is called once for the root vertices, once for the middle vertices and once for the tip vertices to calculate the final vertex position. Result is one generated hair, which form is defined by the three input guide hairs. If the tessellation factor is increased more hairs will be generated, which means more invocations for the TES. Different barycentric coordinate values need to be used for each invocation of the TES with the same input vertices. Figure 30 shows the result of the simple example.

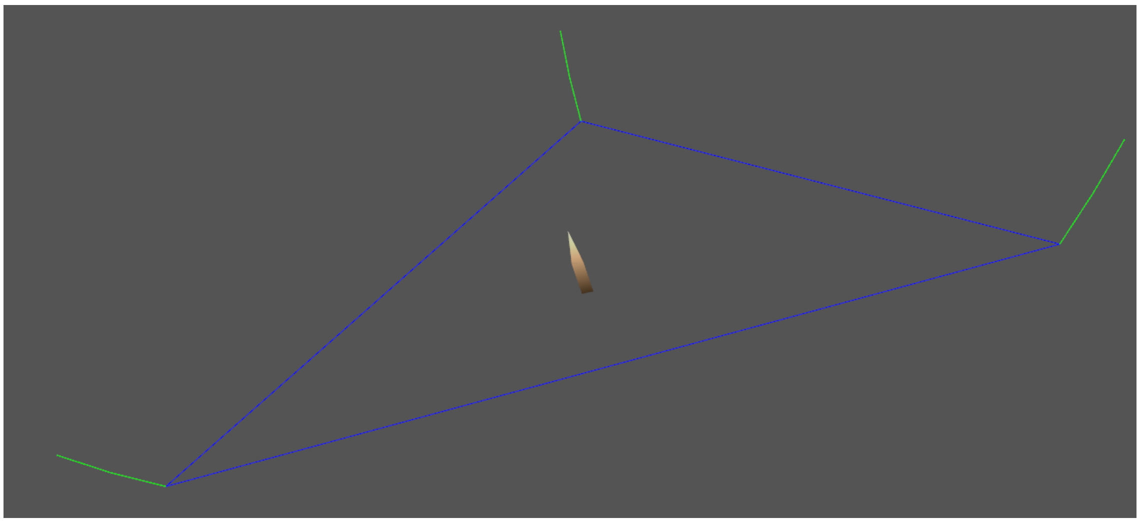


Figure 30: Multi strand interpolation simple example

The barycentric coordinates are calculated once at start up. Two random values between 0.0 and 1.0 are stored into a variable for the first two barycentric coordinates. If the sum of these values is greater than 1.0, the new first barycentric value is the subtraction of the old first barycentric value from 1.0 and the new second barycentric value is the subtraction of the old second barycentric value from 1.0. In the end the first two barycentric values are subtracted from 1.0 to calculate the third barycentric coordinate value.

```
coord1 = Ogre::Math::RangeRandom(0.0, 1.0);
coord2 = Ogre::Math::RangeRandom(0.0, 1.0);

// sum has to be smaller than one to be useful for barycentric coordinates
if(coord1 + coord2 > 1)
{
       coord1 = 1.0 - coord1;
       coord2 = 1.0 - coord2;
}

pStrandCoordinatesFloat[writePosition++] = coord1;
pStrandCoordinatesFloat[writePosition++] = coord2;
pStrandCoordinatesFloat[writePosition++] = 1.0f - coord1 - coord2;
```

Figure 31: Calculation of a random barycentric value

One advantage of multi strand interpolation is that the generated hair covers the whole scalp of the character. The left picture of Figure 32 shows how new generated guide hairs are placed on top of the scalp mesh (blue quad). Additionally, the form of the generated hairs is a mix out of the form of the three guide hairs, which lets every generated hair look slightly different. The nearer a hair is to a guide hair, the more it will look like this hair. Hairs, which are placed in the middle of the triangle are a mixture of all three guide hairs.

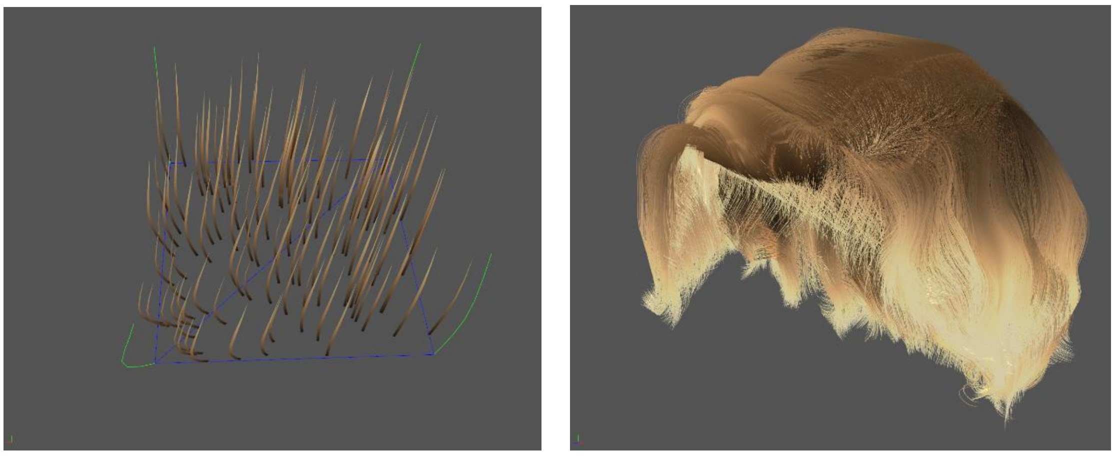


Figure 32: Results multi strand interpolation

There are still two problems with multi strand interpolation. It is not possible to render separated wisps and parting in the hair. First try to solve this problem, was not to render hair segments if the distance between guide hair vertices or the angle between guide hairs was too big. Unfortunately, this experiment did not give the wanted results. Figure

33 shows the results of this attempt. There is a big bold area, were the parting should be and the hair at the position of the separated wisp is just cut off.

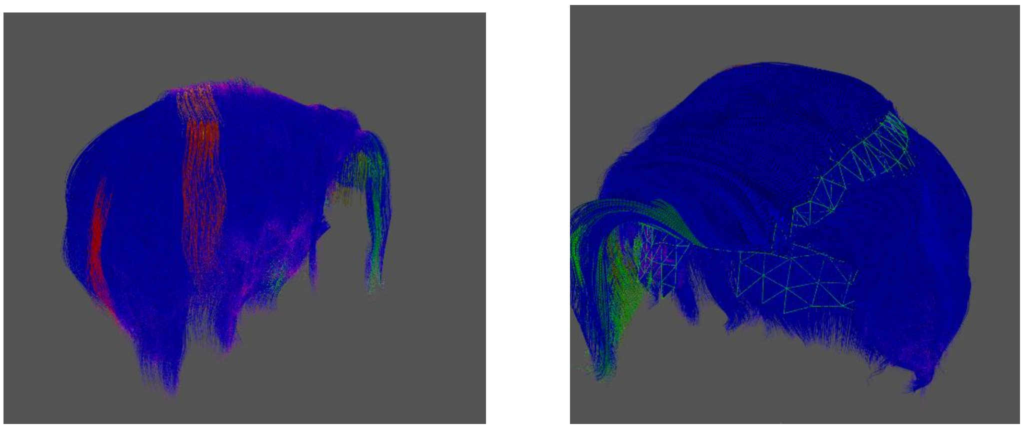


Figure 33: Attempt to fix separate wisp and parting problem

5.4. Combination of Single Strand and Multi Strand Interpolation

The second attempt to fix the separate wisp and parting problem was based on how Tariq implemented collision handling for multi strand interpolation. Her target was not to have to do collision calculation for the generated hairs. But the multi strand tessellation hair always goes through a collision object when this object is between the used guide hairs. The idea of Tariq was to switch to single strand rendering when a collision of the guide hairs with a collision obstacle occurred. Switching between guide strands is also implemented for this solution. Instead of checking for collisions it is checked how far are the guide strand separated from each other and how big the angle between their tangents for their current hair segment are. The maximum distance and the maximum angle are parameters, which can be changed to be able to get the wanted result for the hair style. Figure 34 shows the result from two different perspectives. The separate wisp problem is solved. For the parting of the hair it shows a better result than the previous implementation. However, perfect parting cannot be achieved with this approach. A solution would be to separate the scalp mesh into two parts, with additional guide hairs for the parting area. This would allow to render a parting, with a defined distance, dependent on the distance of the two scalp meshes.

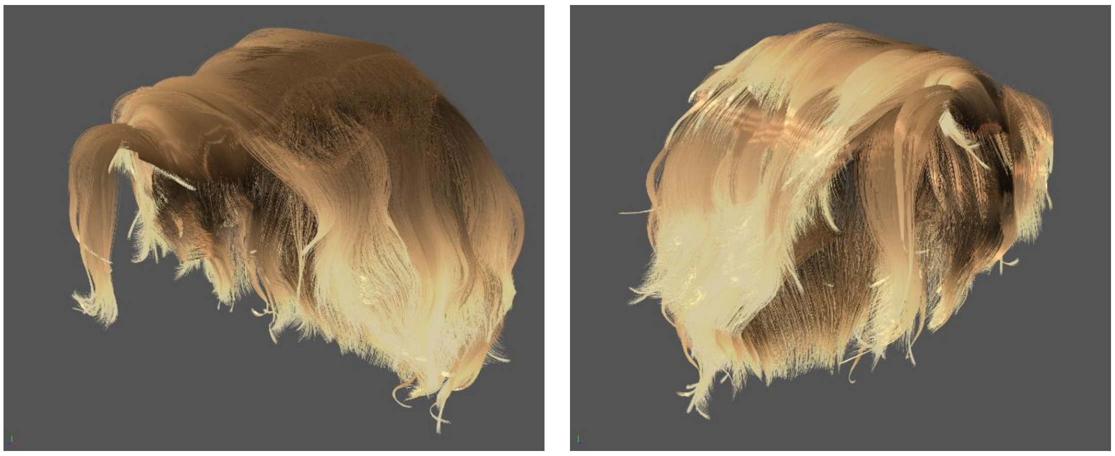


Figure 34: Result of single strand and multi strand interpolation combined

5.5. Handling Different Hair Guide Sizes

Target was to be able to have the possibility of different number of hair segments per hair guide instead of having the same number of hair segments for every hair guide. Since the number of hair segments is directly connected with the performance of hair rendering and also the memory, which needs to be used to save the input data, reducing the number of hair segments for short hair guides and at the same time provide enough hair segments for long hair is reasonable.

As mentioned in section 5.2 different hair guide sizes can easily be handled with single strand interpolation. Only the hair strand size as well as the current position of the hair strand vertex relative to the hair tip needs to be saved. Unfortunately, for multi strand rendering handling different hair strand sizes is not that trivial because three hair guides are used as input. When those three hair guides do not have the same segment number and therefore not the same vertex number, it needs to be handled, which vertices of the hair guides are used for interpolation.

It was tried to handle this problem with three different approaches. The first idea was to use the vertex number of the longest guide strand for the number of invocations for the TCS. It should be interpolated the same way as with uniform guide hair sizes, until the tip vertex of the shortest guide strand. This would mean that all operation stay the same until the tip of the shortest guide strand is reached. For the following interpolations the tip vertex of the shortest guide hair is used. When tip of the next guide hair is reached, the tip vertex of this guide hair is used for the following interpolations until the tip of the last guide hair is reached. This iteration did not work well because hair segments are drawn into each other when the tip of one or two guide hairs is used for multiple multi strand interpolations.

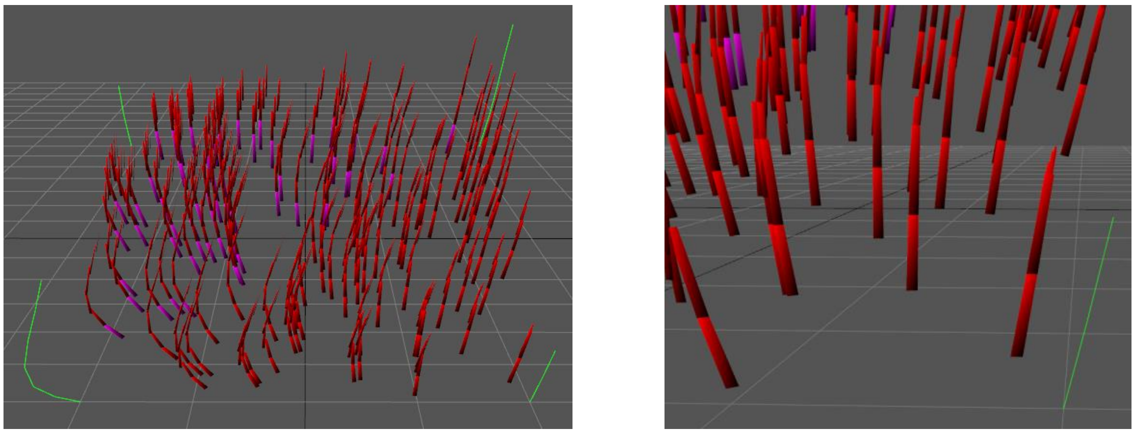


Figure 35: Different hair sizes first iteration

In the second iteration the shortest guide strand vertex count was used for the number of invocations of the TCS. Vertices were used in the same way until the tip of the shortest guide strand was reached. This means that only the same number of vertices of the longer guide strands is used for interpolation as the number of vertices of the shortest guide strand. The rest of the vertices are ignored. The result hairs are drawn correctly. However, this approach also causes a choppy transition from long to short guide strands. It would be better if the transition between different sizes is smooth. Another problem with this approach is that geometric detail of longer guide strands is lost.

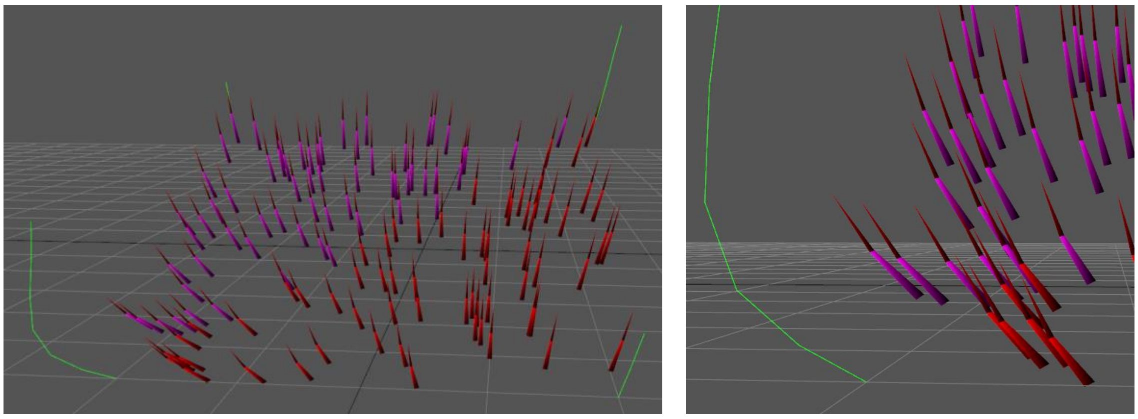


Figure 36: Different hair sizes second iteration

One problem is that the number of vertices that are used for multi strand interpolation has to be the same for every guide strand. With the first iteration it was tried to use all available vertices. The second iteration on the other hand ignored vertices. The third iteration is a middle ground between the first and second iteration. The same amount of vertices will be ignored in iteration three as in iteration two. However, the selected vertices, which are used for interpolation are different. It will always be used the root and the tip vertex. Which vertices are selected in-between is dependent on the vertex buffer size of the smallest guide hair. A delta step value is calculated to retrieve the next used vertex.

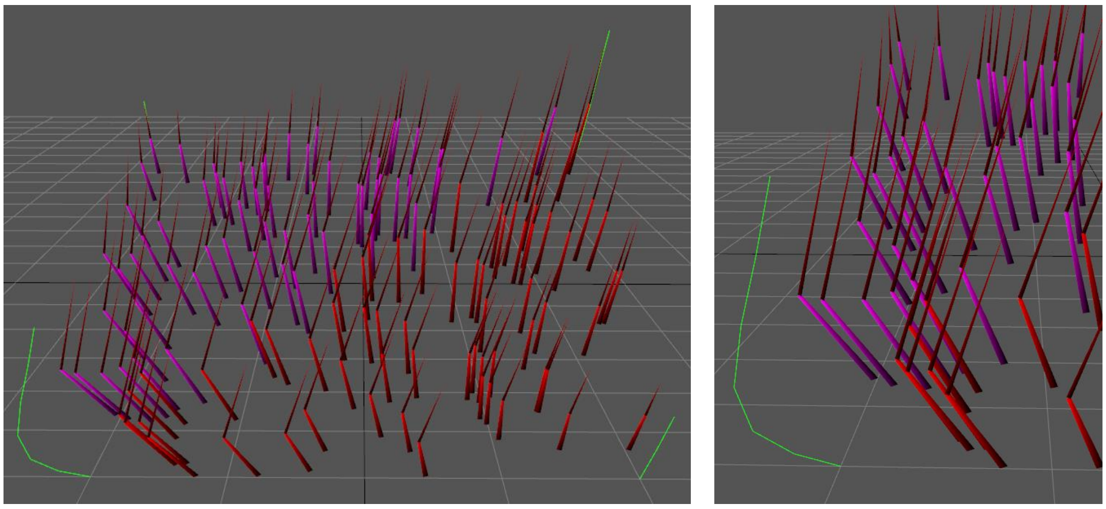


Figure 37: Different hair sizes third iteration

With the third iteration the length of the guide hairs is better represented and it allows a smoother transition from short to long hairs. However, there is still some geometry information lost. This is especially visible if the vertex count difference of the guide hairs is big. If the vertex number of the guide hairs only differs in a small number, the missing of geometry detail is only barely visible.

5.6. Expand Lines into Camera Facing Quads

After the generation of hair within the tessellation stage, the geometry shader is used to expand the isolines into camera facing quads.

The geometry shader is designed for small geometry expansion and therefore efficient for this operation. The reason to expand isolines into camera facing quads is to be able to show hair, which changes is width when it gets nearer to the tip of the hair. This functionality would not be possible with isolines because the width of isolines can only be changed per draw call. Another reason is to be able to change the width of hair dependent on the number of hairs that are generated. If less hairs are generated the width of hair needs to be thicker. With this functionality level of detail for hair can be implemented, which shows less hairs with a thicker width.

The geometry shader gets as input the two vertices of a line segment. First, the eye vector and the tangent of the line segment is calculated. The normalized cross-product of eye vector and tangent results into the offset vector, which is used to calculate the four new vertices of the camera facing quad.

```
vec3 tangent = pos2.xyz - pos1.xyz;
tangent = normalize(tangent);

vec3 eyeVec = (g_mInverseWorldMatrix * g_CameraPosition).xyz - pos1.xyz;
vec3 sideVec = normalize(cross(eyeVec, tangent));

vec3 width1 = sideVec * strandWidth[0];
vec3 width2 = sideVec * strandWidth[1];

// Offset positions to for drawing triangles in world space
vec4 pos11 = vec4( pos1.xyz + width1, 1 );
vec4 pos12 = vec4( pos1.xyz - width1, 1 );

vec4 pos21 = vec4( pos2.xyz + width2, 1 );
vec4 pos22 = vec4( pos2.xyz - width2, 1 );
```

Figure 38: Expansion of isolines into camera facing quads

5.7. Hair Form

With camera facing quads the form of the hair can be adjusted with two width values per segment. These two width values have to be calculated inside the TES per hair vertex and will be send to the geometry shader for the geometric expansion. For the tapering of the hair a simple solution was used, which gives a good result for thin hair and provides the option to define, where tapering of the hair begins.

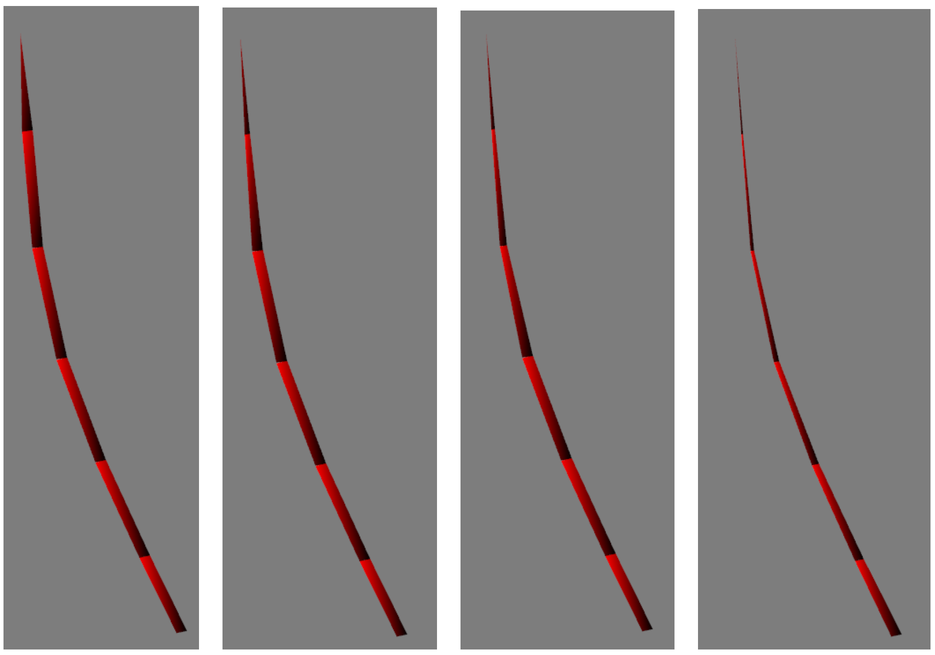


Figure 39: Hair strand tapering (1, 2, 3 and 6 segments)

Result of this implementation is a hair form, which has the same width from root position to the position, where tapering is defined to begin. From there a linear interpolation is used, which reduces the width until it has reached the tip of the hair. At the tip of the hair the width of the hair is 0. Figure 39 shows different hair tapering settings for a hair strand that has the same base width.

5.8. Hair Strand Tessellation

Hair strand tessellation is about how a single hair strand can be tessellated to get a smooth curve at the end. The detail tessellation factor of the OpenGL tessellation stage is needed for this operation. Tariq had a different approach for her hair strand tessellation. She made it in a pre-calculation step within the geometry shader and wrote the result to a buffer, which was used in the following render passes to render the tessellated hair on the screen.

Our implementation of the hair rendering is done in a single draw call, which has the advantage that for every single hair segment of the guide hair a different detail tessellation factor can be applied. This is a crucial functionality to support dynamic view dependent level of detail, which also is dependent on the shape of the hair strand. Important for the used algorithm was that it works with a small amount of input vertices on a per segment basis. Best solution for hair strand tessellation would be an algorithm that just needs the two vertices of a hair segment. Two different techniques for hair strand tessellation were implemented and evaluated.

5.8.1. Hermite Curve Interpolation

The first implementation was hermite curve interpolation [Pipenbrinck 2013]. For the calculation of the result position the starting point P_0, the tangent T_0 at the starting point, the end point P_1 and the tangent T_1 at the end point are needed. For hermite curves the tangents define the smoothness or tightness of the curve. The variable t is defined between 0 and 1. It gives information about the current position in the line segment. If t is 0 it is the start position. If t is 1 it is the end position. Each result position can be calculated with the following equation:

$$H(t) = (2t^3 - 3t^2 + 1)P_0 + (t^3 - 2t^2 + t)T_0 + (-2t^3 + 3t^2)P_1 + (t^3 - t^2)T_1$$

The hermite curve equation is executed in the TES. The input variable `gl_TessCoord.x` exactly provides the information needed for the variable t. The vertices for the start point and the end point are given. However, the tangents need to be calculated at start up out of the hair guide vertices. For the calculation of the tangents the formula for Cardinal splines can be used.

$$T_i = a * (P_{i+1} - P_{i-1})$$

Result is the tangent T_i at the vertex P_i, where P_{i+1} is the next vertex and P_{i-1} is the previous vertex. In this formula, a defines the tightness of the resulting curve. For the special case, which is called Catmull-Rom spline, a is set to 0.5. This results into following equation.

$$T_i = 0.5 * (P_{i+1} - P_{i-1})$$

Catmull-Rom splines were used for the implementation. For the calculation of the tangents of the hair guides vertices, two special cases needed to be handled for the root vertex and the tip vertex. The root vertex has no previous vertex. Instead the root vertex is used for the previous vertex. For the tip tangent calculation the tip vertex is used instead of the next vertex. The calculated tangents are stored in an additional texture and read in the same way as the positions in the TCS.

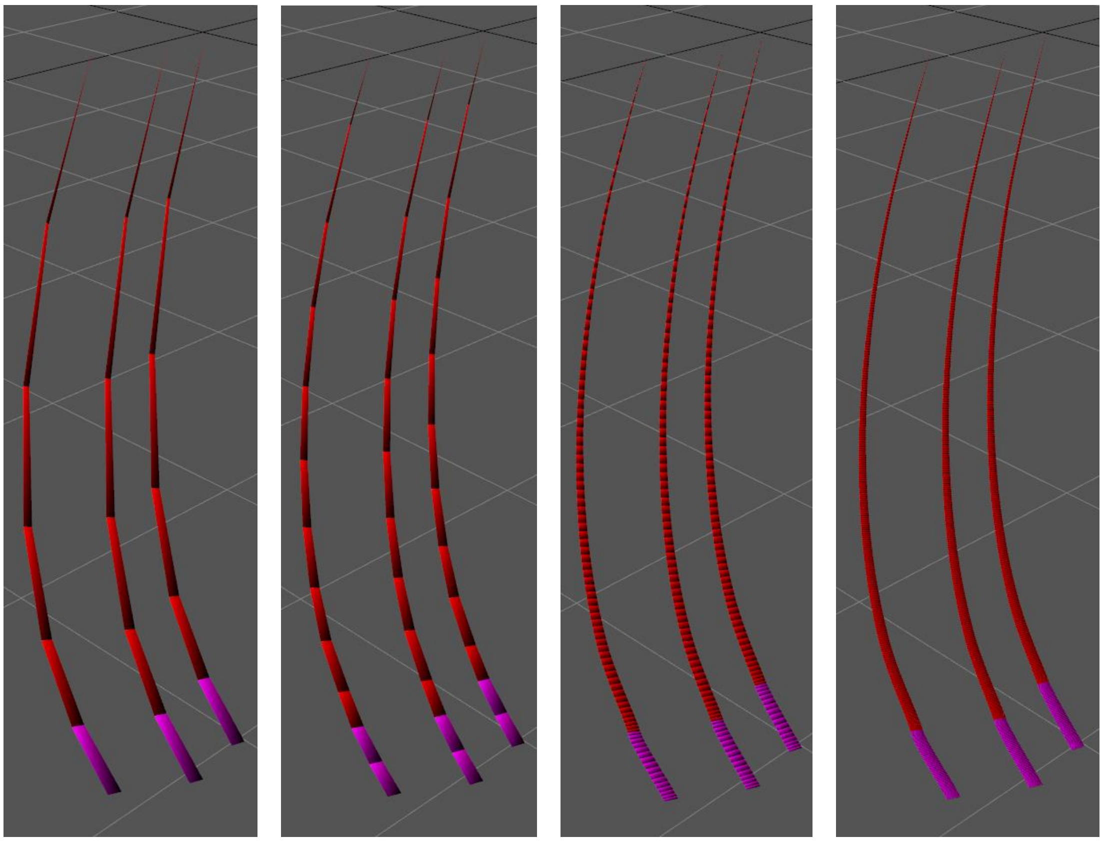


Figure 40: Hermite curve interpolation with detail tessellation factor 1, 2, 16 and 64

Result is a smooth curve, which goes directly through all control points of the hair guide. The problem with the calculation of hermite curves is that there is no documented way how interpolated tangents can be calculated, which are mandatory for the right hair shading calculation in the fragment shader. It is also not possible to calculate the right tangents within the geometry shader because there is only access to the vertices of the current generated line segment. An alternative approach needed to be used, which also allows to calculate interpolated tangents for tessellated hair strands.

5.8.2. Uniform Cubic B-Splines

Tariq used in her implementation uniform cubic b-splines, where she also interpolated the tangents. Uniform cubic b-splines use four vertices as input. The following equation shows how uniform cubic b-splines are calculated [Hamilton 2014].

$$P(u) = \frac{1}{6}\begin{bmatrix} u^3 & u^2 & u & 1 \end{bmatrix} \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix} \begin{bmatrix} P_i \\ P_{i+1} \\ P_{i+2} \\ P_{i+3} \end{bmatrix}$$

The variable u is again the `gl_TessCoord.x`, which is defined between 0 and 1. The main difference is that as input four vertices are needed. These vertices are the control points of the generated curve. P_i is the previous vertex, P_{i+1} is the start vertex, P_{i+2} is the end vertex and P_{i+3} is the next vertex. The root segment of the guide hair as well as the last segment of the guide hair needs to be handled in a different way. For the root segment, the previous vertex P_i is the same as the start vertex P_{i+1}. For the tip segment the next vertex P_{i+3} is the same as the end vertex P_{i+2}. For tangent calculation the following equation is used.

$$T(u) = \begin{bmatrix} u^2 & u & 1 \end{bmatrix} \begin{bmatrix} 0.5 & -1.0 & 0.5 \\ -1.0 & 1.0 & 0.0 \\ 0.5 & 0.5 & 0.0 \end{bmatrix} \begin{bmatrix} T_i \\ T_{i+1} \\ T_{i+2} \end{bmatrix}$$

The three tangents T_i, T_{i+1}, and T_{i+2} can be calculated with:

$$T_i = P_{i+1} - P_i$$

$$T_{i+1} = P_{i+2} - P_{i+1}$$

$$T_{i+2} = P_{i+3} - P_{i+2}$$

The matrix calculation form is efficient to calculate on the GPU. No pre-calculation of tangents is needed. Tangents can be calculated inside the TES, which is especially important for multi strand interpolation because the hair segment is an interpolation of three hair segments and the tangent will be different dependent on the used barycentric coordinates. The results are smooth curves and smooth tessellated tangents.

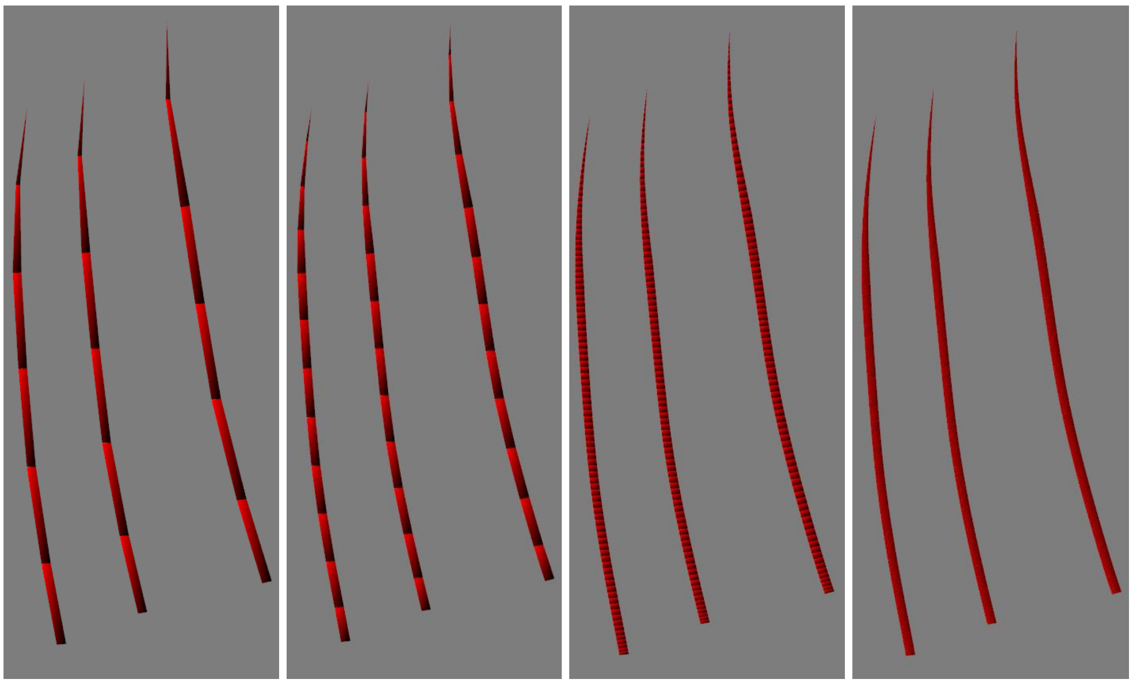


Figure 41: Uniform cubic b-spline interpolation with tessellation factor 1, 2, 16 and 32

One problem is that uniform cubic b-splines cut off a small part of the start and the end of the hair strand. The end parts do not really matter and the root part is so small that it can barely be recognised when rendering hair with thousands of strands for a hair style.

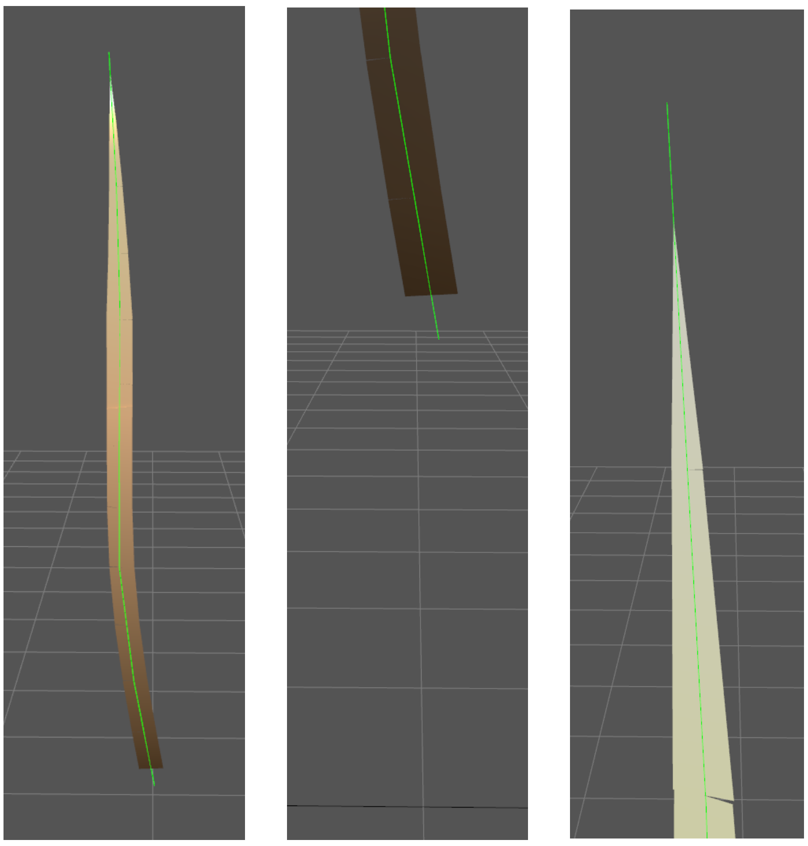


Figure 42: Uniform cubic b-splines start and end segment

5.9. Curly Hair

Realistic curly hair is hard to render. Guide hairs with a huge number of vertices are needed to be able to render curly hair. In real-time there are limited resources and number of guide hair vertices should be as small as possible. However, there is one way to fake curly hair. The idea is to offset the calculated hair vertex in x and z direction dependent on a generated curl deviations texture.

```
int numCVs = 13;
float sd = 1.5f;

int numSegments = numCVs - 3;
int numVerticesPerSegment = ceil( ((m_NumberMaxOfHairSegments+1)*64) /
                                  float(numSegments) );
float uStep = 1.0/numVerticesPerSegment;
Ogre::Vector2* CVs = new Ogre::Vector2[numCVs];
CVs[0] = Ogre::Vector2(0,0); CVs[1] = Ogre::Vector2(0,0);
CVs[2] = Ogre::Vector2(0,0); CVs[3] = Ogre::Vector2(0,0);
float x,y; int index = 0; int lastIndex = 0;

Ogre::Matrix4 basisMatrix = Ogre::Matrix4
(
       -1/6.0f,      3/6.0f,       -3/6.0f,      1/6.0f,
       3/6.0f,       -6/6.0f,      0,            4/6.0f,
       -3/6.0f,      3/6.0f,       3/6.0f,       1/6.0f,
       1/6.0f,       0,            0,            0
);

for (int i = 0; i < numberOfGuideHairs; i++)
{
       //create the random CVs
       for(int j=4;j<numCVs;j++)
       {
              BoxMullerTransform(x,y);
              x *= sd;
              y *= sd;
              CVs[j] = Ogre::Vector2(x,y);
       }
       //create the points
       for(int s=0;s<numSegments;s++)
       {
              for(float u=0;u<1.0;u+=uStep)
              {
                     Ogre::Vector4 basis;

                     basis = basisMatrix * Ogre::Vector4(u*u*u, u*u, u, 1);
                     Ogre::Vector2 position = Ogre::Vector2(0,0);
                     for (int c = 0; c < 4; ++c)
                            position += basis[c] * CVs[s+c];
                     // save position to texture/buffer
              }
       }
       lastIndex = index;
}
```

Figure 43: Creation of curl deviations for curly hair

The texture is generated at start up on the CPU. Adjustable input variables are the number for control vertices `numCVs` and the deviation scale `sd`. The higher the number of hair segments per guide strand, the higher should be the number of control vertices and the deviation scale. Dependent on `numCVs` random control vertices are generated using Box-Muller Transformation. Notice that the first four control vertices are always set to 0. This has the reason that vertices near the root of the hair are not influenced to make sure that the hair still has the original position near the scalp. The number of generated curl deviations per segment is dependent on the maximum tessellation factor and the highest number of guide hair segments. For curl deviation, calculation per sub segment a basis matrix is calculated and multiplied with four different control vertices. These calculations are executed for each hair guide positions to ensure different curl deviations per hair strand. For multi strand interpolation the index count of the scalp mesh divided by three is used, instead of the hair guide count.

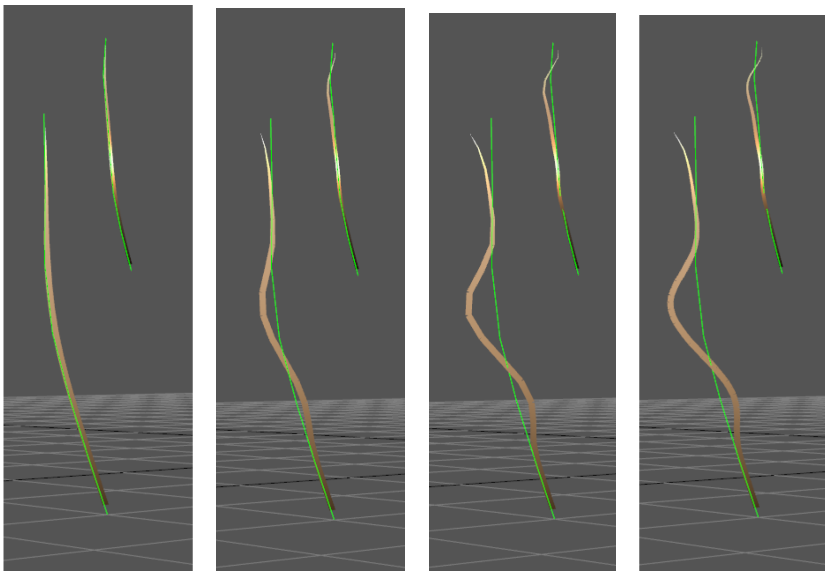


Figure 44: Curly hair results with no curl offset, low curl offset, increased curl offset and increased curl offset with hair strand tessellation

The result is more curvy hair, which is slightly offset in x and z direction. A low curl offset is doable with small amount of subdivisions. The higher the curly hair offset, the more subdivisions of a hair segment is needed to still provide a smooth curve. Therefore, good quality curly hair is still processing intensive to render on the GPU.

5.10. Thinning

Especially with single strand interpolation all hairs have the same overall length as the corresponding guide hair. In multi strand interpolation the length of the hair is dependent on the three input guide hairs. For some hair styles, hairs with the same length can be the wished result. However, there are also hair styles, where hairs are thinned. The result are hairs, which have a slightly different size. Hair dresser often use this to make thick hair look thinner. Thinning is the functionality to support this feature for a hair style. The variable `g_thinning`, which is defined between 0.0 and 1.0 is used to control the amount of thinning for the hair.

```
// calculate data and write to texture and array
m_strandLength = new float[m_numStrandVariables];

float minLength = 0.2f;

for (int i = 0; i < m_numStrandVariables; ++i)
{
       m_strandLength[i] = Ogre::Math::RangeRandom(0.0, 1.0) * (1-minLength) +
                            minLength;
       pFloat[writePos++] = m_strandLength[i];
}
```

Figure 45: Random strand length generation

At start up a random generated texture is created with a predefined number of variables. 1024 random values have proven to be enough for this implementation. First the minimum length is defined. Afterwards the random generated length values are saved into a texture.

```
//thinning the hair lengths
float strandLengthPosition = float(iMasterStrand & (g_numStrandVariables-1)) /
                              g_numStrandVariables;
float inLengthFrac = texture( TexStrandLength , strandLengthPosition ).r;
// percentage of max length
float maxLength = 1.0-g_thinning + g_thinning*inLengthFrac;

float cutOfLength = hs_currentNumOfGuideHairSegments –
       (maxLength * hs_currentNumOfGuideHairSegments);

// add LOD to strand width
float tmpStrandWidth = g_strandWidth * g_strandWidthLOD;
// Make hair strand thinner from defined position to top
if( lengthToRoot > (maxLength * hs_currentNumOfGuideHairSegments) )
{
       strandWidth = 0.0;
}
else if( (hs_strandPosition - gl_TessCoord.x) <=
         (g_strandTaperingStart+cutOfLength) )
{
       float ignoredPositions = hs_currentNumOfGuideHairSegments –
              (g_strandTaperingStart+cutOfLength);
       strandWidth = tmpStrandWidth *
              (maxLength - ( ( hs_currentNumOfGuideHairSegments –
              ignoredPositions - hs_strandPosition + gl_TessCoord.x ) /
              (hs_currentNumOfGuideHairSegments - ignoredPositions) ) );
}
else
{
       strandWidth = tmpStrandWidth;
}
```

Figure 46: Thinning in TES and adjustment of hair tapering

In the TES the calculated, predefined strand length is read in and applied dependent on `g_thinning`. The maximum length of the current hair strand is calculated. Dependent on the maximum length the tapering of the hair is adjusted. If the current length to the root vertex is greater than the maximum length, the width of the hair strand is set to 0.

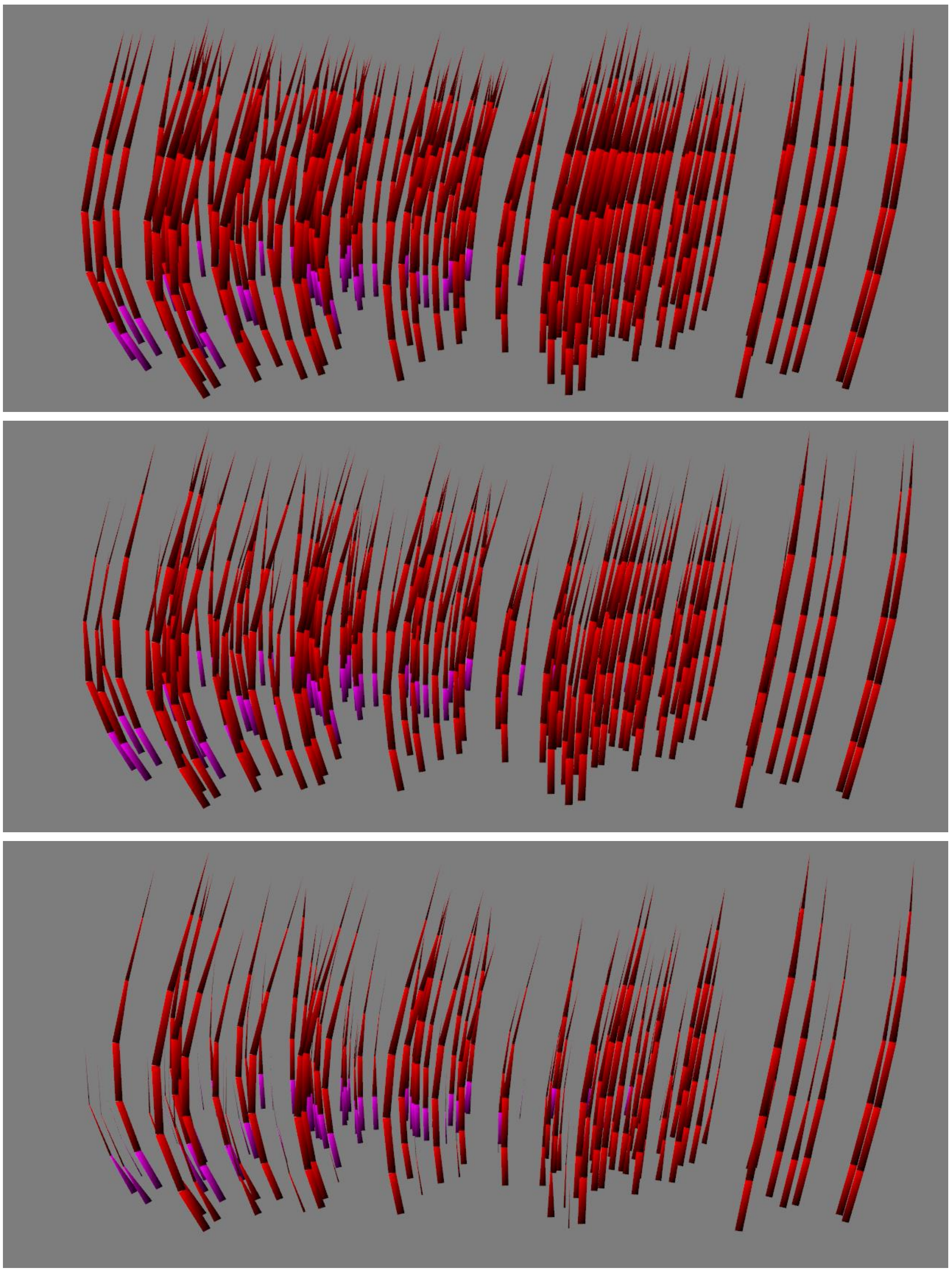


Figure 47: Thinning with value 0.0, 0.5 and 1.0 (top to bottom)

5.11. Random Deviations

The look of the hair styles, the current hair rendering system generates, is too uniform and too predictable. All hairs strands are perfectly aligned either clamp based with single strand interpolation or evenly distributed with multi strand interpolation. All the hairs strands look like as they were perfectly styled. Real human hair behaves differently. It can often be observed that some hair strands are separated from the other hairs strands. Especially at the edges of the hair style, single hair strands are visible, which have a different form than the neighbouring hair strands. It almost never happens that every hair follows the same form. There are very often a small amount of hairs that have another form. Random deviations is an attempt to bring randomness into a hair style to get a more realistic result, which can be better compared with a real-world hair styles.

The implementation of random deviations is similar to the creation of curly hairs. Adjustable input variables are the number for control vertices `numCVs`, the global deviation scale `sdScale` and a deviation scale `sd`, which is set dependent on the wished deviation of a hair strand. The main difference for random deviations compared to curly hair is the added randomness. The deviation scale `sd` chances dependent on a random value. With a probability of 60%, hairs are not modified at all. Only 5% of the hair have high `sd` value, which leads to stray hair. 15% of hair are lesser stray hair. For the remaining 20% small random deviations are only applied near the tips. For the offset of the tips the thinning scale `m_thinning` is used. The different `sd` values are applied for the control vertices creation. The offset position calculations in x and z direction are calculated the same way as for curly hair and saved into a texture. For the hair strands that were not modified, a zero vector is saved to the texture.

```
float sdScale = 1.0f;

for (int i = 0; i < m_numStrandVariables; i++)
{
	float randomChoice = Ogre::Math::RangeRandom(0.0, 1.0);
	if(randomChoice>0.6)
	{
		float maxLength = (1.0-m_thinning) +
		m_thinning*m_strandLength[i%m_numStrandVariables];
		int maxCV = floor(maxLength*numSegments)+ 2;

		//create the random CVs
		for(int j=2;j<numCVs;j++)
		{
			float sd;

			if(randomChoice > 0.95)//make some very stray hair
				sd = 1.2f;
			else if(randomChoice > 0.8)
				sd = 0.8f;
			else // some lesser stray hair (more deviant near tip)
			{
				if(maxLength>((numCVs-1)/numCVs) && j==numCVs-1)
					sd = 100.0f;
				else if(j>=maxCV)
					sd = 4.0f;
				else
					sd = 0.12f;
			}

			BoxMullerTransform(x,y);
			x *= sd * sdScale;
			y *= sd * sdScale;
			CVs[j] = Ogre::Vector2(x,y);
		}

		//create the points
		for(int s=0;s<numSegments;s++)
		{
			for(float u=0;u<1.0;u+=uStep)
			{
				Ogre::Vector4 basis;
				basis = basisMatrix *
				    Ogre::Vector4(u * u * u, u * u, u, 1);
				Ogre::Vector2 position = Ogre::Vector2(0,0);
				for (int c = 0; c < 4; ++c)
					position += basis[c] * CVs[s+c];
				// save position to texture/buffer
			}
		}
	}
	else
		// no deviations, save 0 position to texture
}
```

Figure 48: Creation of random deviations

Result is added randomness to the hair, which makes the overall hair style more realistic and believable. Figure 49 shows three different deviations settings of one hair style to demonstrate the difference between hair without deviations and hair with deviations enabled.

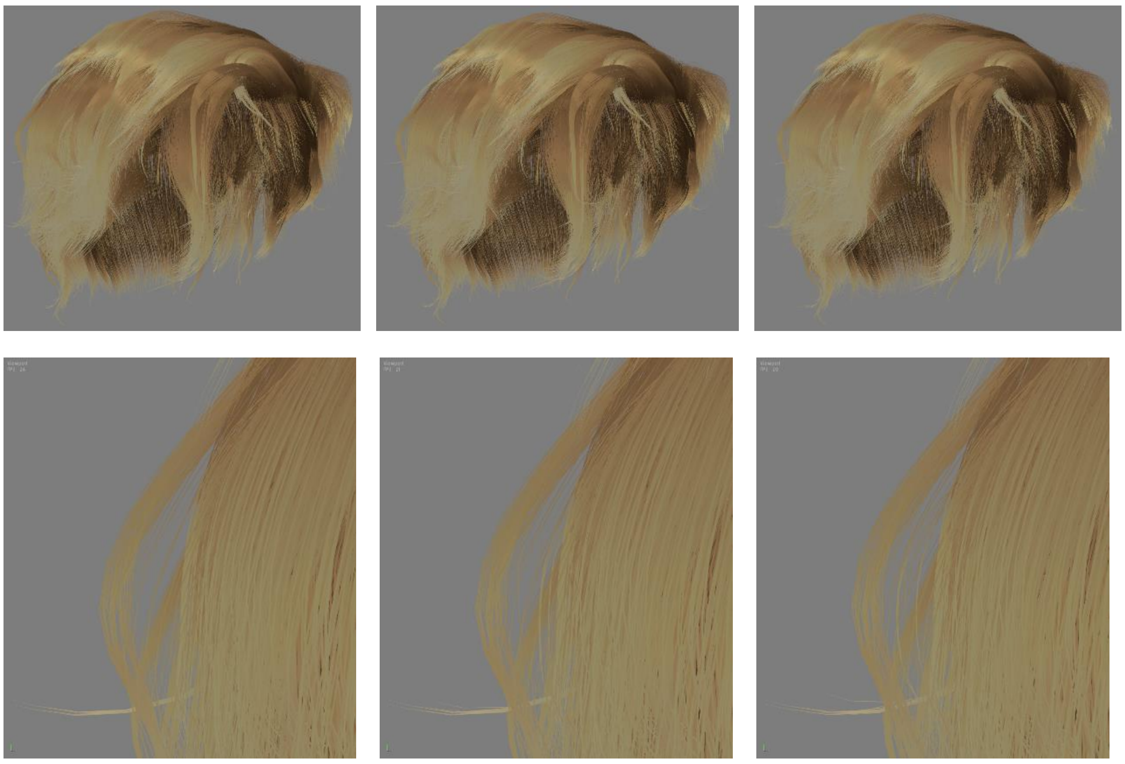


Figure 49: Hair style (full hair and zoomed) with random deviation scale 0, 0.025 and 0.05 left to right

5.12. Level of Detail

LOD for the hair rendering system is an important part to adjust the amount of generated hair and smoothness of the hair dependent on the available computing resources of the GPU. LOD is often done distance dependent. For the research project it made no sense to implement a distance dependent LOD because the camera distance never changes. Instead a LOD slider was implemented, which has a value between 0.0 and 2.0. The interval from 0.0 to 1.0 adjusts the number of generated guide strands and at the same time decreases the width of single guide strand with increased value. Is the value between 1.0 and 2.0, the detail tessellation factor is increased, which improves the smoothness of the hair. This LOD slider is also useful for the research project to be able to render less detailed hair with a thicker width and therefore get a more abstract representation of the hair style.

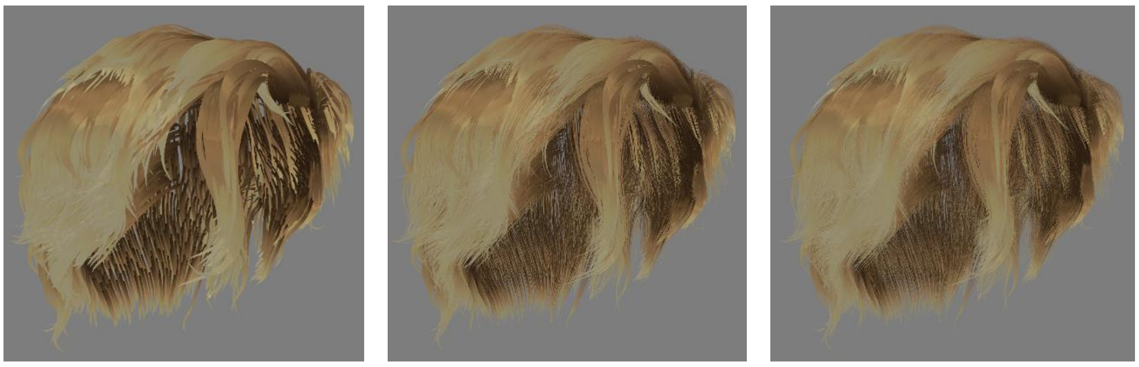


Figure 50: Hair with LOD slider set to 0.1, 0.5 and 1.0

Result is a simple modification of the tessellation factors dependent on a slider value. This works perfectly fine for the amount of generated hair. However, the amount of needed processing power increases dramatically with increased detail tessellation factor. The problem here is that all hair segments are subdivided in the same way even if the hair is straight, where subdivision of hair does not give additional geometric detail. There is a potential to save computing resources, without the loss of geometric detail.

5.12.1. Screen Space Adaptive Level of Detail

The idea of screen space adaptive level of detail (SSALOD) is to have a dynamic detail tessellation factor for each hair strand segment, which is dependent on the shape of the hair and the size of a hair segment in screen space. The calculation of the detail factor in the TCS is done once per hair segment. The two vertices of the hair segment are transformed into screen-space to get the size of the hair segment. According to this size the detail tessellation factor is calculated. Additionally, the form of the hair strand is taken into account for the calculation of the detail factor. As pre-calculation step, the angle between the previous segment and the current segment, as well as the angle between current segment and the next segment is calculated. The larger angle is then used in the shader to influence the final detail factor.

Configuration options for SSALOD are the screen segment size of a hair strand segment, the meaningful bend angle and the maximum bend angle. The meaningful bend angle describes the angle above which detail tessellation should be applied. Is the angle between hair segments smaller than the meaningful bend angle no subdivision should be performed. The maximum bend angle defines the angle between hair segments, where maximum subdivisions of hair segments should be performed. All three options can be modified dependent on the available processing power and the anticipated smoothness of the hair.

Result of this technique are hair strands with different tessellated hair segments. Screen space size setting 15 gives a smooth result for the example hair strands with only a small number of subdivisions per hair strand.

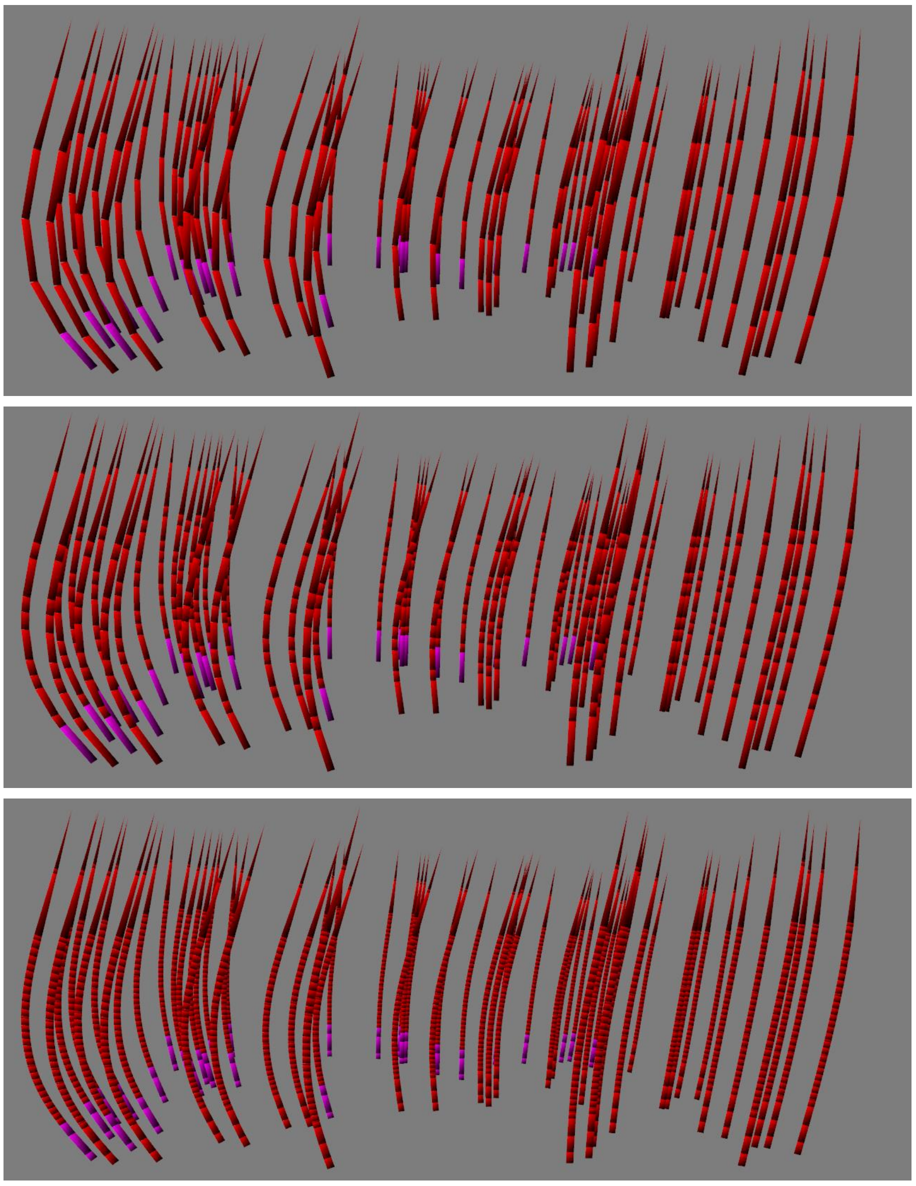


Figure 51: Example of SSALOD with bend angle minimum 5, bend angle max 45 and hair segment screen space size of 40, 15 and 4 from top to bottom.

5.12.2. Hair Culling

Another way to save computing resources is not to generate and tessellate hair strands, which are not visible. These calculations can also be done in the TCS. The implemented solution for this character rendering system uses the normals of the scalp mesh to decide if hairs should be generated or not. A slider was added, which controls the amount of culled hairs. If hairs are culled, which are visible to the viewer, is dependent on the created guide hairs and it cannot be guaranteed that visible hairs are not culled. Therefore, this slider needs to be adjusted carefully. For short hair it is less likely that hairs are culled, which are visible. In this case the culling value can be set higher.

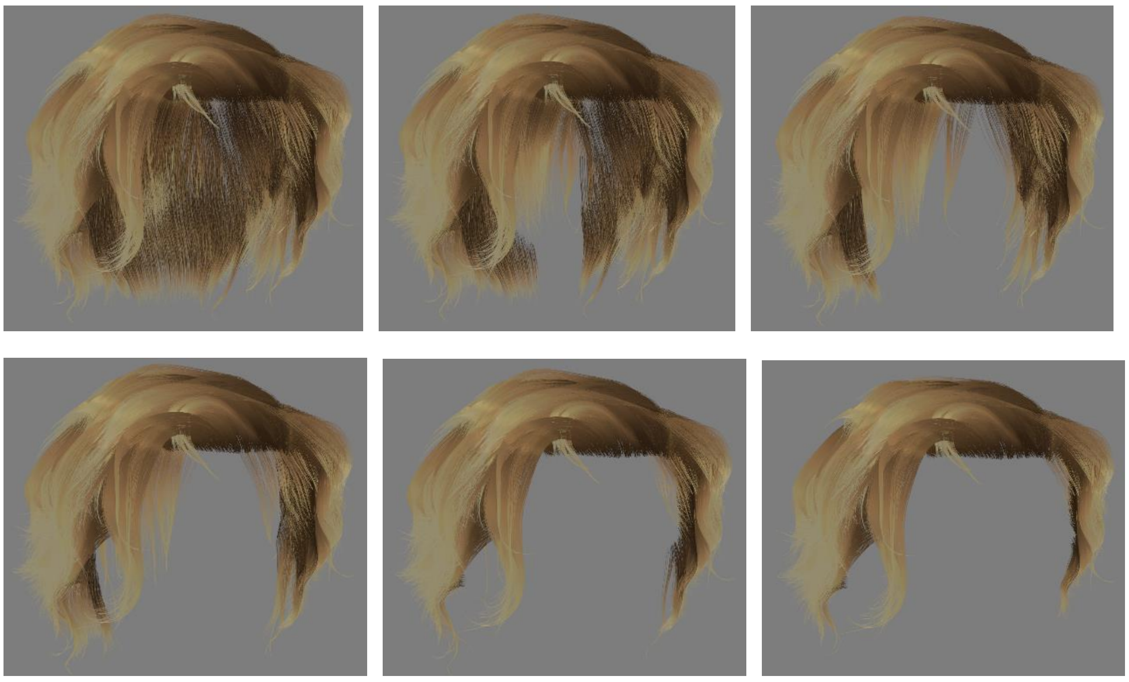


Figure 52: Hair culling with culling scale 0.0, 0.2, 0.4, 0.6, 0.8 and 1.0

5.13. Hair Shading

Previous sections were concerned with the geometric generation of hair. Another important part of high quality hair is the shading of the hair. For hair shading Filmakademie Baden-Württemberg has already implemented a hair shading algorithm based on [Sadeghi et al. 2010; Zinke and Weber 2007]. In this section this implemented shading algorithm is explained. This algorithm has been ported to glsl and is used for the generated hair.

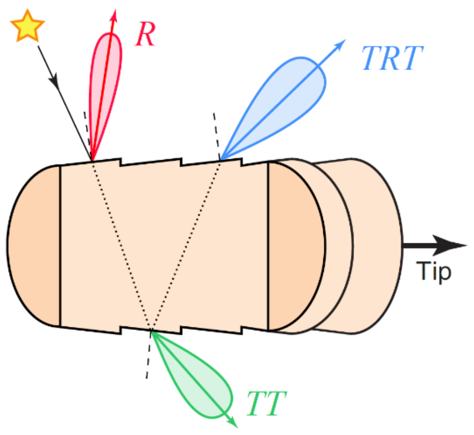


Figure 53: Hair model [Sadeghi et al. 2010]

[Sadeghi et al. 2010] added to physically based shading model artistic friendly controls. Their implementation is based on [Marschner et al. 2003]. The hair is represented as a translucent cylinder with tilted cuticles. These cuticles have the effect that the single scattering of the hair has three subcomponents. These subcomponents are the primary highlight (R), the secondary highlight (TRT) and rim light (TT). Figure 53 shows the different paths light can take through a hair fibre. The primary highlight is from light that is directly reflected. Therefore, the colour of the primary highlight is the same colour as the light. The secondary highlight comes from light that was absorbed by the hair fibre, reflected internally and appears next to the primary highlight. The secondary highlight is nearer to the tip than the primary highlight. The colour of the hair influences the colour of the secondary highlight. The rim light happens when light is transmitted through the hair fibre. In a backlighting situation a bright halo is shown around the hair. This effect is described with TT. Preferably, artists want to be able to modify the primary highlight, the secondary highlight and the rim light.

```
vec3 lightDir = normalize(light_positions[i] – gs_worldPos).xyz;
float lightVec = dot(lightDir, gs_tangent);
float viewDepSpec = dot(gs_viewDir, gs_tangent);

float theta_h = asin(lightVec) + asin(viewDepSpec);
float cosPhi_i = dot(normalize(lightDir – lightVec*gs_tangent),
       normalize(gs_viewDir – viewDepSpec*gs_tangent));

// R (reflection) component
vec3 reflectionColor = clamp(
       _AM_c_R * pow( abs(cos(theta_h - _AM_s_R)) ,reflectWidth ) , 0.0, 1.0);

// TRT component
vec3 transRefTransColor = clamp(
       _AM_c_TRT * pow( abs(cos(theta_h - _AM_s_TRT)),scatterWidth ),
       0.0, 1.0);

// TT component
vec3 transTransColor = clamp(_AM_c_TT * max(0.0, cosPhi_i) *
       pow( cos(theta_h - _AM_s_TT) , transmitWidth ), 0.0, 1.0);

// diffuse component
vec3 diffColor = clamp(_AM_d * sqrt(min(1.0, lightVec*lightVec)) +
(gs_strandPosition * tipColor + gs_strandPosition * rootColor), 0.0, 1.0);

fragColor.xyz += (diffColor + reflectionColor + transTransColor +
       transRefTransColor) * light_colors[i].xyz * lightPower;
```

Figure 54: Hair shading glsl code

Our implementation allows artist to change colour, strength, width and shift of the R, TT and TRT component. Additionally, it is possible to change the diffuse, root and tip colour of the hair. For every light in the scene the code of Figure 54 is executed. Calculation is done based on the tangents of the hair. First, the light direction is calculated with the position of the light and the position of the hair. Afterwards the angles θ and φ are calculated. With these angles and the artist controlled input variables the R, TT, TRT and diffuse colour are calculated. In the end all components are added together for the final colour.

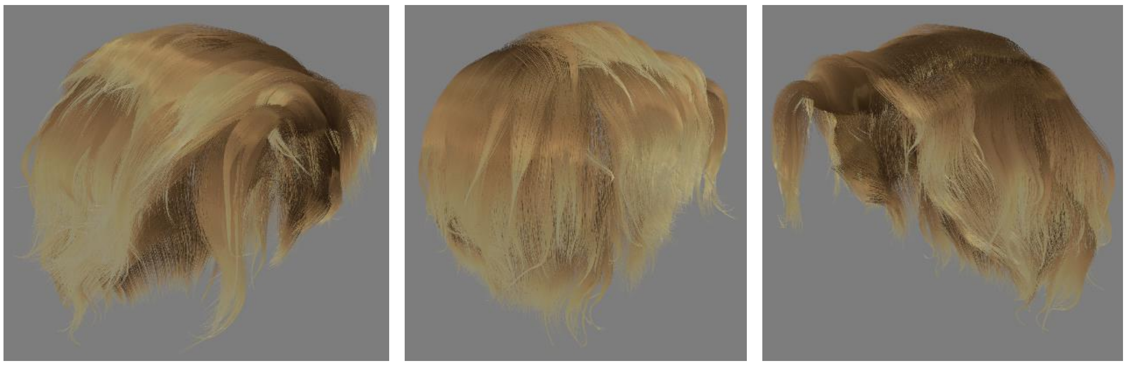


Figure 55: Sara hair style with hair shading

6. Character Rendering System Integration

The character rendering system is implemented in the open source framework of Filmakademie Baden-Württemberg called Frapper. It uses Qt for the graphical user interface and Ogre3D for graphics rendering including animations. Frapper is node based. Different nodes inside Frapper provide different functionalities. Two tasks were required to put the developed hair rendering system and the previous work that has been done for character rendering together. The first task was to create a node, which provides the functionality for the hair rendering system. This node is described in the next subsections. The second task was to translate the Cg shader for character rendering into glsl.

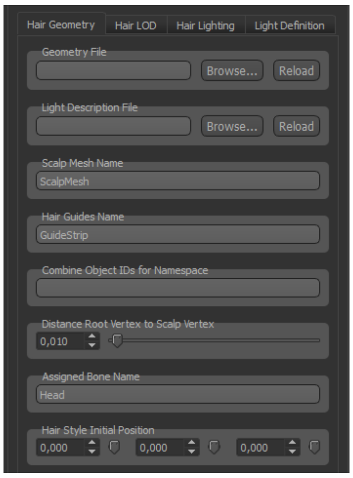
Character rendering has previously been done with a different node called `AnimatableMeshNode`. This node inherits from `GeometryAnimationNode`, which provides functionality to produce 3D geometry and play animations.

For the hair rendering system a custom node was created, which provides all adjustable inputs and functionality. This node is called `AnimatalbeMeshHairNode`. It is used to load the character geometry including the hair geometry. For each character there is one mesh file created, which includes all geometric information for face, eyes, teeth, clothes, eye brows, eyelashes, scalp mesh and guide hairs. Additionally, the node is used inside Frapper to modify input parameter of the different geometries. For `AnimatalbeMeshHairNode` input configurations were added to be able to modify the hair style. This section gives an overview about all input variables and their effect for hair rendering. The `AnimatalbeMeshHairNode` is subdivided in four tabs called **Hair Geometry**, **Hair LOD**, **Hair Lighting** and **Light Definition**.

6.1. Hair Geometry

The first tab **Hair Geometry** is concerned with all input values, which directly influence the form of the hair geometry. First input value is the **Geometry File**. Here the character mesh with all the geometry data needs to be selected. **Light Description File** is for a txt file, which includes the data of all light sources. With this file different lighting settings can be loaded in the scene in a fast way without having to add and place each individual light. Light description files have usually 8 to 16 lights included.

The next two string based input parameters are **Scalp Mesh Name** and **Hair Guides Name**. These two inputs are important for the right selection of the scalp mesh and the guide vertices. All geometry in the mesh file is stored as submeshes. When the mesh file is selected and the mesh is loaded, these submeshes are searched for the scalp mesh and all the hair guides. Submesh names must contain these strings, which were set as input



Geometry File

Light Description File

Scalp Mesh Name: ScalpMesh

Hair Guides Name: GuideStrip

Combine Object IDs for Namespace

Distance Root Vertex to Scalp Vertex: 0,010

Assigned Bone Name: Head

Hair Style Initial Position: 0,000 0,000 0,000

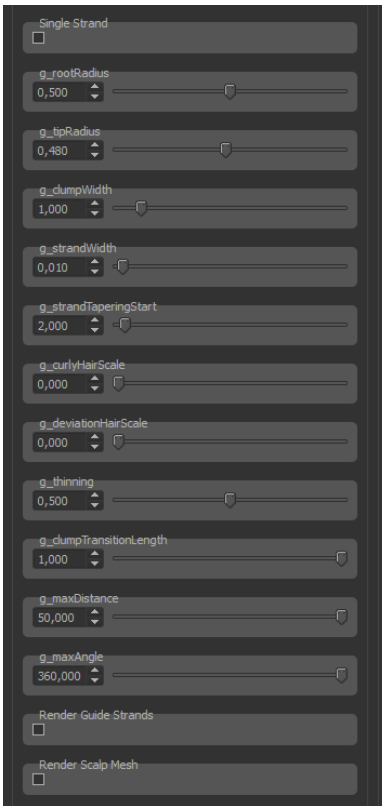
Figure 56: Hair geometry part1

of **Scalp Mesh Name** or **Hair Guides Name**, that the `AnimatalbeMeshHairNode` is able to select the right submeshes when the mesh is loaded. If the scalp mesh or guide hairs are not found in the load mesh method, an error will be logged and the mesh will not be rendered. It is also important to keep in mind that the number of indices of the scalp mesh have to be the same as the number of guide hairs. Only then hair can be loaded and multi strand interpolation is rendered correctly.

The following input value **Distance Root Vertex to Scalp Vertex** is a slider to configure the distance the root vertex of a hair guide can have to a scalp vertex and still be recognised as the corresponding hair guide. This functionality was added for the case when the root vertices of the hair guides are not exactly placed on the vertices of the scalp mesh.

Assigned Bone Name is the name of the bone the hair style is assigned to. This assignment is done to support hair style movement relative to a bone when animation is applied to it. **Hair Style Initial Position** defines the initial position of the hair style relative to the bone position.

Single Strand is a check box to enable single strand rendering. If this input parameter is not selected, the hair will be rendered with multi strand interpolation. The mesh needs to be reloaded before the different hair interpolation method is applied. The slider **g_rootRadius**, **g_tipRadius** and **g_clumpWidth** are single strand interpolation specific parameters. **g_rootRadius** defines the maximum radius around the guide hair in which single strand interpolated hairs can be generated. **g_tipRadius** has the same functionality only for the tip of the hair. With modifying **g_rootRadius** and **g_tipRadius**, it can be defined how the distance of interpolated hair strands changes from the root to the tip of the hair. It can often be observed that hair moves together at the tip of the hair to build combined, clump based hair strands. **g_clumpWidth** scales the radius of **g_rootRadius** and **g_tipRadius**.



Single Strand: ☐

g_rootRadius: 0,500

g_tipRadius: 0,480

g_clumpWidth: 1,000

g_strandWidth: 0,010

g_strandTaperingStart: 2,000

g_curlyHairScale: 0,000

g_deviationHairScale: 0,000

g_thinning: 0,500

g_clumpTransitionLength: 1,000

g_maxDistance: 50,000

g_maxAngle: 360,000

Render Guide Strands: ☐

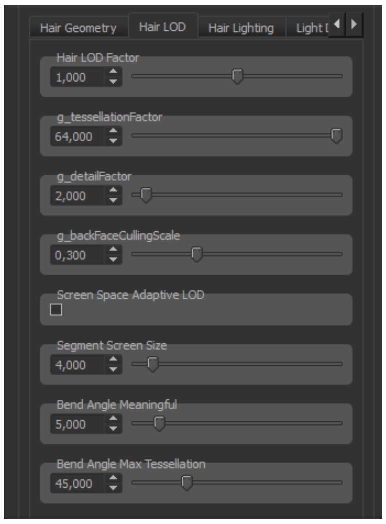
Render Scalp Mesh: ☐

Figure 57: Hair geometry part 2

The following five parameter are used for single and multi strand interpolation. The input parameter to change the width of the hair is **g_strandWidth**. It defines the minimum width of the hair. Tapering of the hair can be modified with **g_strandTaperingStart**. This slider defines at which distance relative to the tip of the hair strand tapering starts. This distance is counted in vertices. Next the input parameter **g_curlyHairScale**, **g_deviationHairScale** and **g_thinning** are provided. These are the scale parameters for curly hair, hair deviations and thinning.

The last three sliders are the input values to configure the combination of multi strand and single strand interpolation. **g_clumpTransitionLength** defines how long the transition phase between single and multi strand interpolation is. The distance of two hair guides when single strand interpolation should be performed is configured with **g_maxDistance**. If the distance between two hair guides is under this value, multi strand interpolation will be used. **g_maxAngle** handles the maximum angle between guide hairs. At the end there are two check boxes **Render Guide Strands** and **Render Scalp Mesh** to enable and disable rendering of guide hairs and scalp mesh.

6.2. Hair LOD



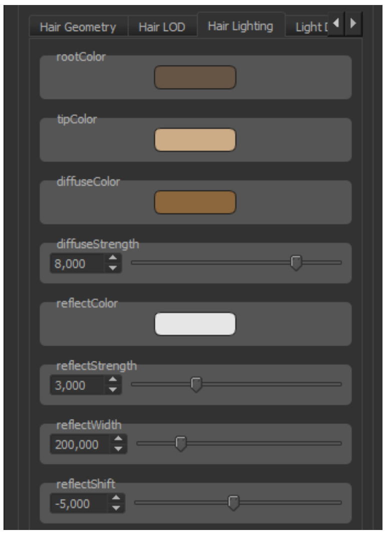
Hair LOD Factor 1,000
g_tessellationFactor 64,000
g_detailFactor 2,000
g_backFaceCullingScale 0,300
Screen Space Adaptive LOD ☐
Segment Screen Size 4,000
Bend Angle Meaningful 5,000
Bend Angle Max Tessellation 45,000

Figure 58: Hair LOD

The second tab **Hair LOD** provides all level of detail settings, which can be applied to the hair rendering. First is the **Hair LOD Factor**, which changes the level of detail of the hair. Between 0.0 and 1.0 the hair number and width is modified. Between 1.0 and 2.0 the detail tessellation factor is increased. **g_tessellationFactor** is the slider to control the number of generated hairs per TCS invocation. **g_detailFactor** is the input value for the number of subdivisions per guide hair segment. Hair culling can be configured with the input value **g_backFaceCullingScale**. The value 1.0 is here maximum culling.

SSALOD can be enabled and disabled with **Screen Space Adaptive LOD**. Is SSALOD enabled changes to the detail tessellation factor will have no effect. SSALOD can be configured with **Segment Screen Size**, **Bend Angle Meaningful** and **Bend Angle Max Tessellation**. **Segment Screen Size** defines the size a hair segment should have in screen space. Dependent on this value the detail tessellation factor is calculated. **Bend Angle Meaningful** and **Bend Angle Max Tessellation** are configurations for form dependent tessellation. They define the angle between hair segments, which is meaningful enough to start hair segment subdivision and the angle were the maximum amount of subdivisions should be applied.

6.3. Hair Lighting



rootColor

tipColor

diffuseColor

diffuseStrength 8,000

reflectColor

reflectStrength 3,000

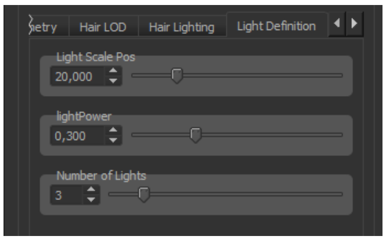
reflectWidth 200,000

reflectShift -5,000

Figure 59: Hair Lighting

Hair Lighting is concerned with all the hair shading input values. Basic colours of the hair, which can be defined are **rootColor**, **tipColor** and **diffuseColor**. These colour values set the hair colour of the hair roots, the hair colour of the hair tip and the overall diffuse colour of the hair. The next input parameters are subdivided into parameters to change the R, the TRT and the TT component of the hair. For each of these components the colour, strength, width and shift can be modified. The input values for R start with reflect, the input values for TRT start with scatter and the input values for TT start with transmit.

6.4. Light Definition



Light Scale Pos 20,000

lightPower 0,300

Number of Lights 3

Figure 60: Light Definition

The last tab is **Light Definition**, which consists of all lighting specific values. The position of the lights can be modified with **Light Scale Pos**. This value scales the position of the created point lights. The intensity of the light can be set with **lightPower** and the number of used lights for the geometry is set with **Number of Lights**. The rendering performance of the hair is directly dependent on the number of lights that are set in the scene. The more lights are used the higher is the fragment shader load for hair rendering.

7. Hair Rendering Performance Analysis

In this section the developed hair rendering system is evaluated for performance and compared against the NVIDIA Fermi Hair Demo [NVIDIA 2010b] and AMD TressFX11 v2.0 [AMD 2013]. Graphics card, which was used for this test is a NVIDIA Geforce GTX 580 [NVIDIA 2010a]. The CPU of the test hardware was a 6 core Intel Xeon X5660 with a core speed of 2.80 GHz [Intel 2010]. NVIDIA Nsight 4.1 [NVIDIA 2014a] and Fraps 3.5.99 [Beepa 2013] functioned as profiling tools. NVIDIA Nsight allows to profile frames and to analyse single draw calls. With this tool 5 frames were captured per test application and the average result is taken for comparison. Fraps can record the frame rate of the application over a predefined time and gives as result the lowest, highest and average frame rate. The frame rate of all three applications were recorded for 60 seconds.

Application	**Frapper Hair**	**NVIDIA Fermi Hair**	**AMD TressFX11 v2.0**
Guide hairs	335	166	21809
Rendered hairs	37632	<29440	65427
Hair segment count	30	between 6 and 40	13 or 10
Hair segment subdivision	2	2	not supported
Lighting	1 point light	1 directional light	1 point light
Shadows	not supported	disabled	disabled
Simulation	not supported	disabled	disabled
Resolution	1284x1058	1024x768	1024x768

Table 1: Test application setup

The setup of the three applications is shown in Table 1. Frapper Hair is our implemented hair rendering system. Sara's hair style was used for this test. Hair culling was set to 0.3. Her hair style is the most similar hair style to the ones of the NVIDIA Fermi Hair and the AMD TressFX11 v2.0 demo. It was tried to make the conditions as near as possible. The NVIDIA Fermi Hair demo and AMD TressFX11 v2.0 were not modified in code. For NVIDIA Fermi Hair demo scene rendering, simulation and shadows were disabled. The hair render count for the NVIDIA demo cannot precisely be counted. Reason for this is that Tariq implemented in her demo a scalp texture, which influences the maximum amount of rendered hair dependent on the position of the generated hairs to save resources. The generated hairs are less than 29440 hairs, which is the maximum amount of generated hairs for the provided hair style input data. In the AMD TressFX demo it was possible to disable the HUD, simulation and self-shadowing. The 21809 hair strand input data is copied twice to triple the amount of rendered hair per frame.

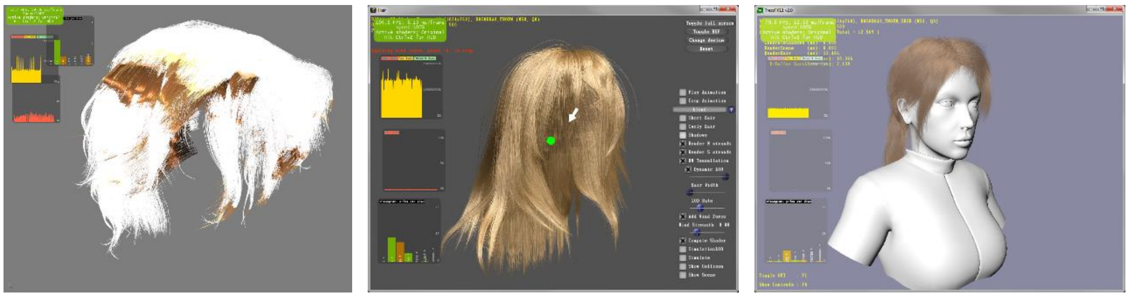


Figure 61: Test application setup NVIDIA Nsight

The test application setup for test with NVIDIA Nsight is shown in Figure 61. The hair styles in all demos were positioned once and 5 different frames were captured, which were analysed in NVIDIA Nsight. Only draw calls for hair rendering were recorded and had an impact on the results. Node that for our implementation the hair shading is not rendered correctly. This result of the hair shading only happens in the NVIDIA Nsight graphics debugger. If Frapper hair rendering is started in a standalone application the hair shading is correct.

Application	**Frapper Hair**	**NVIDIA Fermi Hair**	**AMD TressFX11 v2.0**
GPU time avg/min/max [µs]	17989/17977/17993	4676/4556/4695	9992/9990/9993
CPU time avg/min/max [µs]	128/107/615	<1/<1/<1	<1/<1/<1
Number draw calls	1	6	1
Primitives	17640	1252	1201764
Shaded pixel count avg/min/max	4739814/4699632/ 4758640	2896233/2877888/ 2908336	3819635/3786960/ 3844624
Shaded pixel coverage avg/min/max	347% / 344% / 349%	365% / 362% / 367 %	485% / 481% / 488%
Bottleneck top three average %	36.46% Rasterizer 32.11% L2-Cache 10.47% Blending and Z-Buffer	33.49% Rasterizer 31.22% L2-Cache 8.20% Blending and Z-Buffer	60.20% Rasterizer 24.04% Shading 18.78% L2-Cache
Utilization top three average %	31.42% Shader 25.84% Frame Buffer 16.33% Rasterizer	26.92% Shader 22.09% Frame Buffer 13.62% Rasterizer	41.13 % Shader 19.37% Frame Buffer 12.04% Z-Culling
Shader Type	0% Vertex 4.27% TCS 34.08% TES 13.06% Geometry 48.55% Fragment	0.01% Vertex 0.32% Hull 19.00% Domain 22.64% Geometry 57.87% Pixel	12.90% Vertex 0.0% Hull 0.0% Domain 0.0% Geometry 87.42% Pixel

Table 2: Results NVIDIA Nsight profiler

The Frapper hair implementation is less performance optimized than the other two test applications. Interesting is the spend CPU time. Only the measurements of the CPU time suffered from huge differences in the results. Therefore the slowest and fastest measurement was ignored for the average CPU time. The draw call of Frapper hair uses 128 μs render time, while the other application are under 1 μs for their spend CPU time.

AMD TressFX11 v2.0 is the application, which renders the hugest amount of hairs, while using the highest number of primitives per draw call. The NVIDIA hair demo uses the smallest amount of primitives. Hair rendering is done in 6 draw calls. The shortest time took the NVIDIA Fermi Hair demo to render. However, the rendered hair count is smaller than for the other test applications, which is the main reason for the short GPU time. Main bottleneck for all three implementation is the rasterizer. This is no surprise because there is a huge number of triangles that need to be rasterized. The second highest bottleneck of AMD TressFX11 v2.0 is shading. If it is possible to do more shading optimizations, performance can be improved further. However, it better utilizes the L2 cache compared to the other implementations.

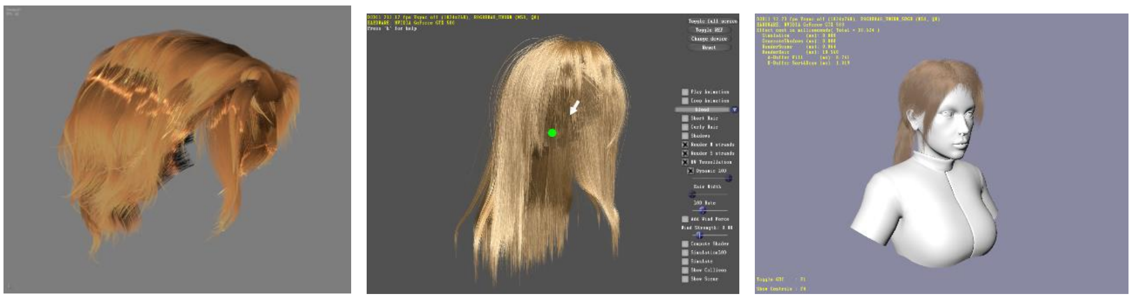


Figure 62: Test application setup Fraps

The second test was performed with Fraps. The frame rate was recorded over the time duration of 60 seconds. Results of this test are the average, minimum and maximum frame time.

Application	**Frapper Hair**	**NVIDIA Fermi Hair**	**AMD TressFX11 v2.0**
Frames per second avg/min/max	62.983/62/64	212.517/209/215	92.833/91/95

Table 3: Results Fraps profiling

This test shows that NVIDIA Fermi Hair takes 43.68% of the time it takes to render AMD TressFX11 v2.0. The Frapper hair rendering still cannot compete with the other hair rendering algorithms, but has a slight improvement for the average rendering time.

Afterwards, more tests were made for the Frapper hair rendering with different detail tessellation factors and SSALOD activated. The test shows, that the increase of the detail factor reduces the performance drastically. SSALOD gives for the test view good results, which are near the render time of the detail factor. The highest visual difference is between detail factor 1 and detail factor 2 for the test view. In Figure 63 these differences are still hard to recognize. Especially the hairs at the edge of the hair style are smoother. Higher detail factors only make sense for this hair style when the camera has a smaller distance to the hair. Node that for this setting, the hair style with SSALOD enabled and a screen segment size of 15 is near the performance of the test with detail factor 1.

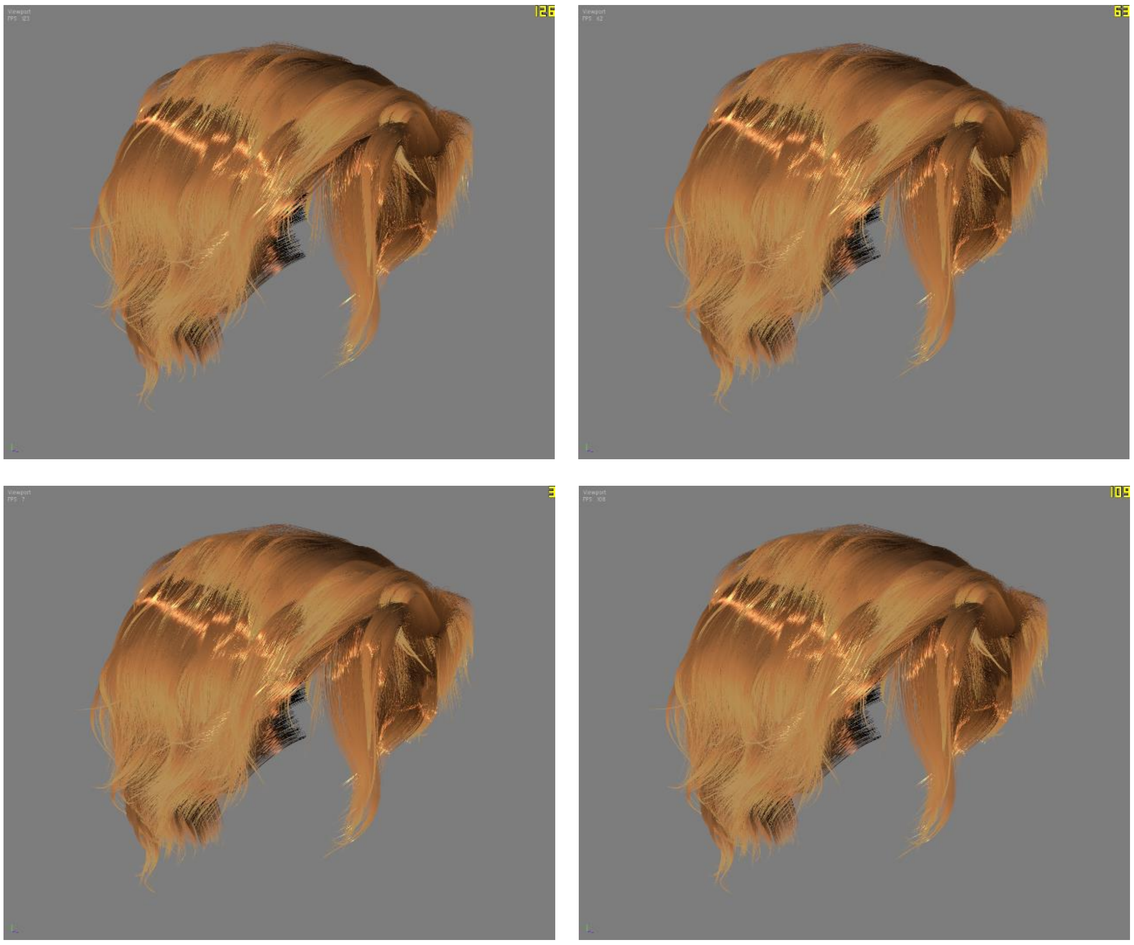
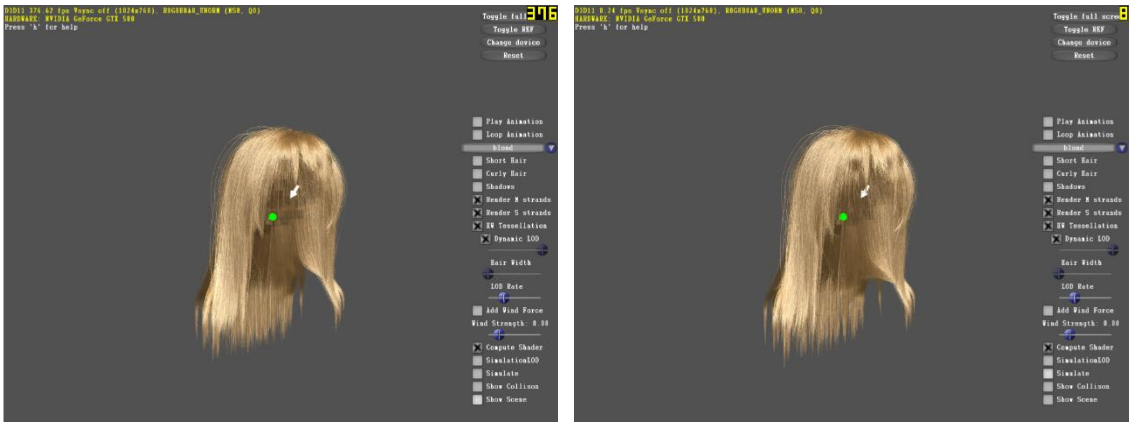


Figure 63: Comparison Sara hair style detail factor 1 (top left), detail factor 2 (top right), detail factor 64 (down left) and SSALOD with segment screen size 15 (down right)



```
D3D11 376.62 fps Vsync off (1024x768), R8G8B8A8_UNORM (MS8, Q0)
HARDWARE: NVIDIA GeForce GTX 580
Press 'h' for help
```

```
D3D11 8.24 fps Vsync off (1024x768), R8G8B8A8_UNORM (MS8, Q0)
HARDWARE: NVIDIA GeForce GTX 580
Press 'h' for help
```

Figure 64: NVIDIA Fermi hair demo setup Fraps detail factor 1 (left) and detail factor 64 (right)

Settings	**Frames per second avg/min/max**		
	Sara	**Gunnar**	**NVIDIA Fermi**
Detail factor 1	125.450/125/126	173.200/172/174	377.567/374/381
Detail factor 2	62.983/62/64	78.717/78/79	233.483/230/234
Detail factor 16	11.467/11/12	13.800/13/14	32.717/32/34
Detail factor 32	6.283/6/7	7.667/7/8	16.483/17/16
Detail factor 64	3.300/3/4	4.033/4/5	8.250/8/9
SSALOD, segment screen size 40	109.617/109/110	172.417/172/173	not supported
SSALOD, segment screen size 15	109.050/108/110	172.467/172/174	not supported
SSALOD, segment screen size 4	93.633/93/94	165.367/165/167	not supported

Table 4: Sara/Gunnar/NVIDIA Fermi hair style results Fraps profiling with different tessellation settings

For comparison with a short hair style, another test was done in Fraps with the Gunnar hair style. The Gunnar scalp mesh has a face count of 782, which results into a maximum of 50048 generated hairs. The settings of the hair are the same as for Sara's hair style. Only the maximum distance and the maximum angle for transition into single strand interpolation had to be adjusted for better visual results. The hair segment count is 24. Especially, for short hair the number of used segments could be reduced to optimize performance further.

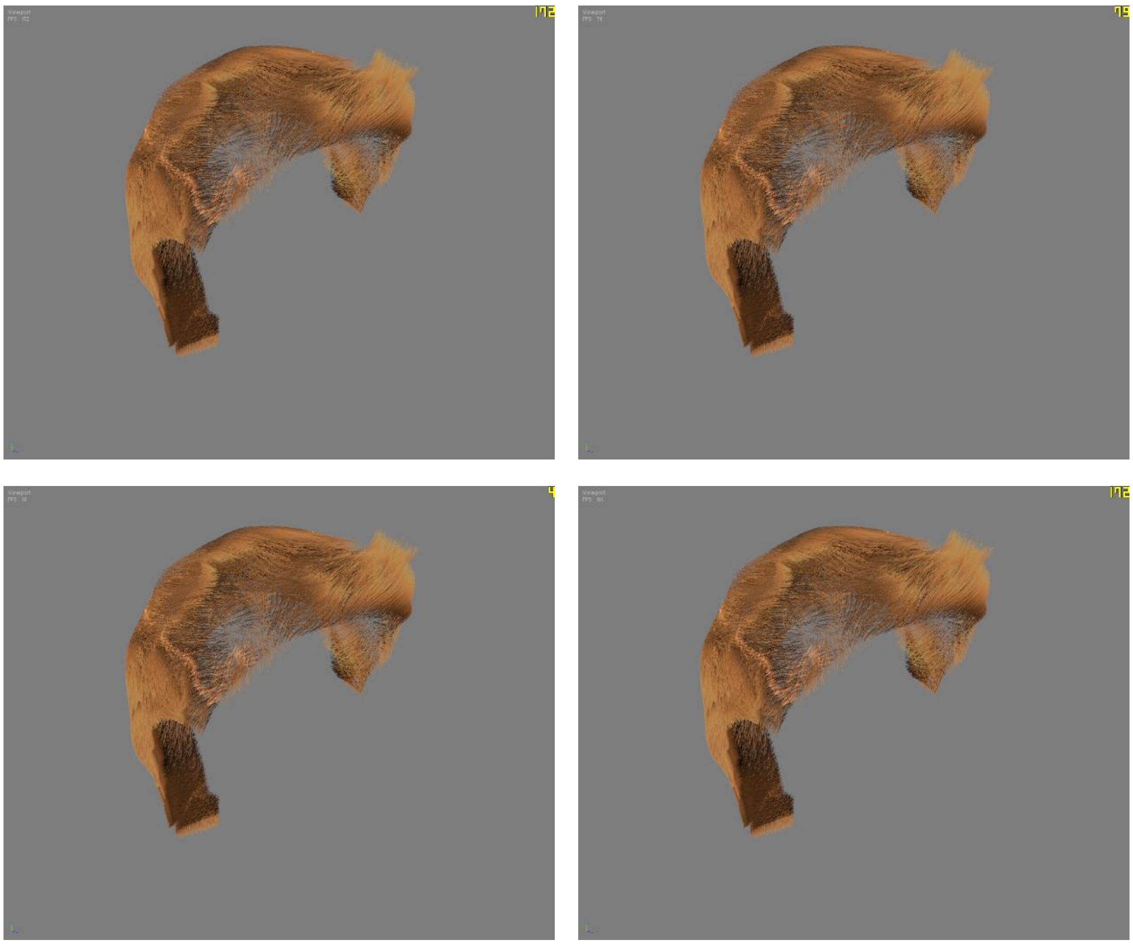


Figure 65: Comparison Gunnar hair style detail factor 1 (top left), detail factor 2 (top right), detail factor 64 (down left) and SSALOD with segment screen size 15 (down right)

The result of Gunnar hair style test is an increased performance compared to Sara's hair style. This is an interesting result because for Gunnar 18768 hair segments and for Sara only 10050 hair segments need to be processed. The reason for this increased performance is the visual size of the hair. Sara's hair style covers more screen space than Gunnar's hair style. This leads to more pixels that need to be shaded.

To support the previous claim another test was done with NVIDIA Nsight using this time the Gunnar hair style. The results are shown and compared to the result of the Sara hair style test in Table 5. First, less pixels are generated on screen. The Gunnar hair style has only 51.80% of the shaded pixel count of the Sara hair style. This leads to a smaller shaded pixel coverage, which reduces load on the rasterizer. Shader type distribution also changes slightly. There is less work to do for the TCS, TES and fragment shader. The geometry shader load increases 2.71%.

Application	**Frapper Hair Sara**	**Frapper Hair Gunnar**
GPU time avg/min/max [µs]	17989/17977/17993	12629/12621/12634
CPU time avg/min/max [µs]	128/107/615	121/104/122
Number draw calls	1	1
Primitives	17640	18768
Shaded pixel count avg/min/max	4739814/4699632/4758640	2455338/2442640/2470128
Shaded pixel coverage avg/min/max	347% / 344% / 349%	180% / 179% / 181%
Bottleneck top three average %	36.46% Rasterizer 32.11% L2-Cache 10.47% Blending and Z-Buffer	33,67% L2-Cache 14,95% Rasterizer 9,09% Z-Culling
Utilization top three average %	31.42% Shader 25.84% Frame Buffer 16.33% Rasterizer	28.77 Shader 18,71% Frame Buffer 10,44% Z-Culling
Shader Type	0% Vertex 4.27% TCS 34.08% TES 13.06% Geometry 48.55% Fragment	0% Vertex 4.21% TCS 31.98% TES 15.77% Geometry 48.0% Fragment

Table 5: Sara/Gunnar results NVIDIA Nsight profiler

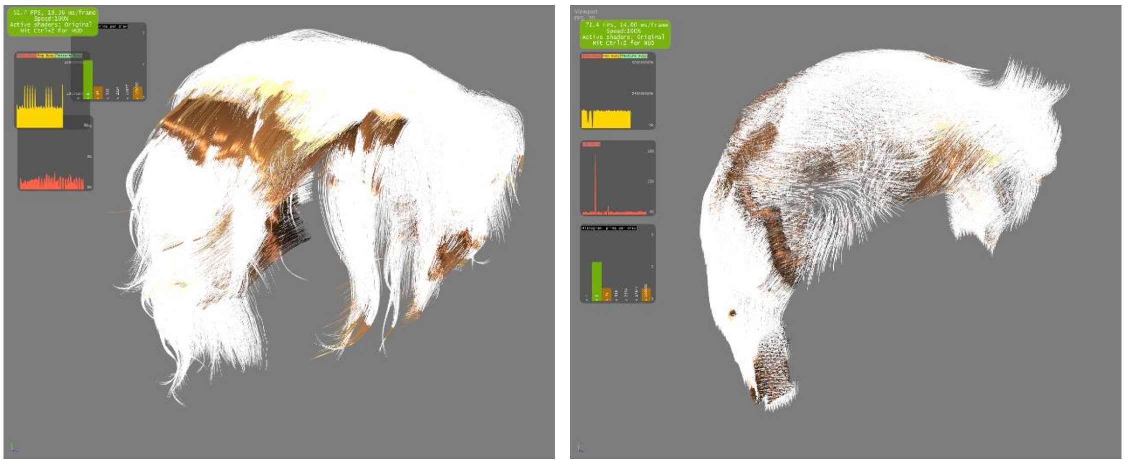


Figure 66: Test application setup NVIDIA Nsight Sara and Gunnar hair style

Both hair styles of Sara and Gunnar were compared with the NVIDIA Fermi hair implementation in respect to performance for hair segment subdivision. NVIDIA Fermi hair demo gives the better results for uniform subdivision of the hair segments. Frapper hair rendering can keep up with the NVIDIA demo when SSALOD is enabled. For a small amount of subdivisions the NVIDIA Fermi hair demo is the better solution, but for higher detail SSALOD gives the better performance.

Overall, the ability to modify detail tessellation per fragment comes with a cost, which can be compensated with SSALOD. The Frapper hair rendering has still possible areas of improvements. First, the amount of hair segments can be reduced to increase performance. Nevertheless, this comes with reduced detail of the hair. Shader code can still be optimized to make better use of the L1 cache and therefore reduce the L2 cache bottleneck. On the plus side the Frapper hair rendering system allows smooth high quality hair at close up view of the hair. SSALOD can also increase the frame rate with reduced hair segments. AMD TressFX11 v2.0 is the fastest implementation. It has the cost of larger hair guide counts, less controllability about the level of detail and does not allow the subdivision of hair segments. The NVIDIA Fermi hair demo allows to save performance with the limitation of hair strand generation in predefined areas. For small hair segment subdivision it gives the better performance. But it is not possible to change the subdivision for every hair segment independently. This functionality allows the Frapper hair rendering and is therefore the better solution for rendering smooth hairs at close distances.

8. Conclusion

Result of thesis is an implementation of a hair rendering system using the OpenGL 4 tessellation pipeline. The hair rendering system was integrated into the framework Frapper and utilizes the Ogre OpenGL 3+ renderer. Single strand and multi strand interpolation was combined in one draw call to generate a more realistic hair look with additional artistic control. The developed algorithm can handle hair guides with different hair segment count. The tapering of the hair is adjustable. Additional features are curly hair, random deviations and thinning. Furthermore, a level of detail system has been implemented to cull hair, which is not seen and to adjust hair segment subdivision dependent on the form of the hair and size of a hair segment projected into screen space. This level of detail system is called SSALOD. The rendered hair uses an artist friendly hair shading algorithm, which allows artist to modify the appearance of primary highlight, the secondary highlight and rim light.

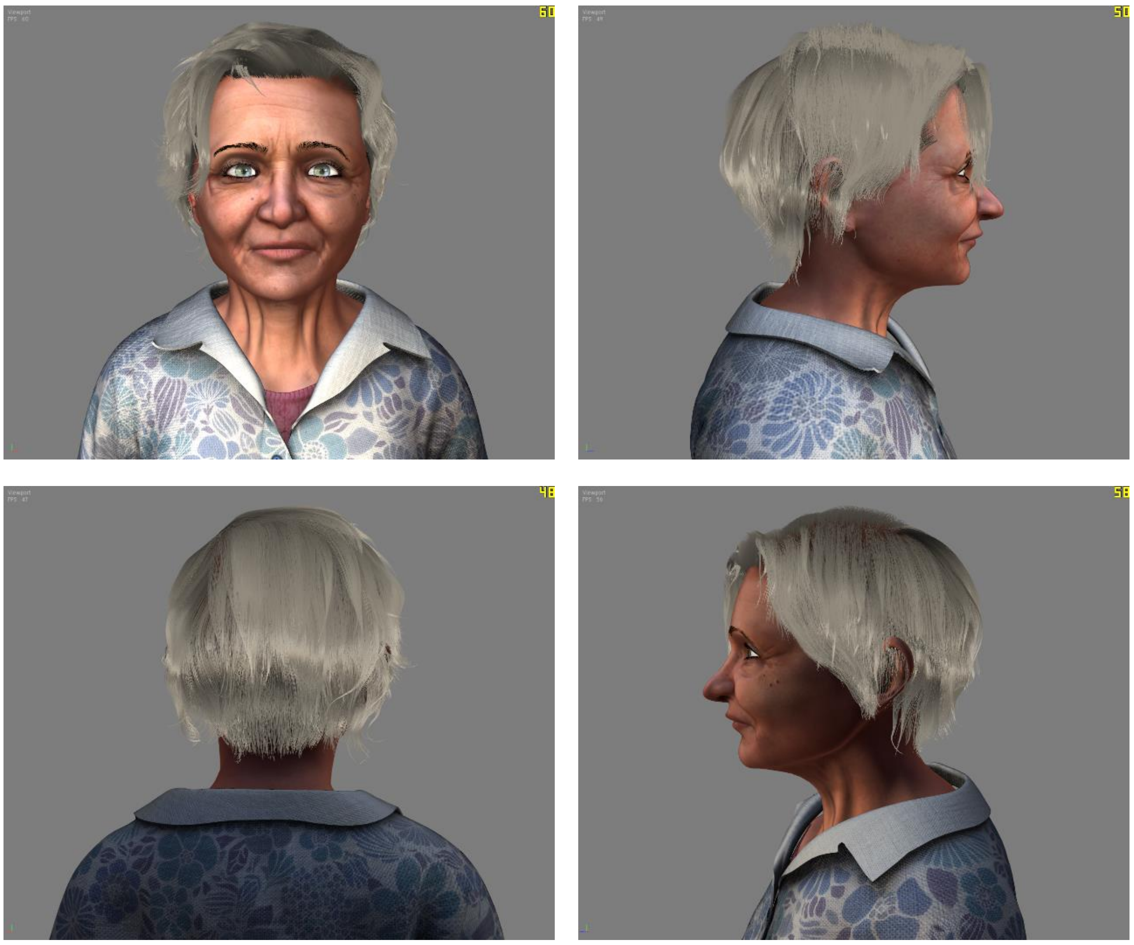


Figure 67: Character Sara with new hair rendering system

The developed hair rendering system was integrated into the Frapper character rendering pipeline converting the existing Cg shader into glsl shader. As test character served the Sara character. In the future the Animation Institute of Filmakademie BW plans to include this hair rendering system for their other characters Gunnar, Nikita and Hank.

Performance of this algorithm was compared against [AMD 2013] and [NVIDIA 2010b]. The results are that the AMD's and NVIDIA's algorithm have the better performance for hair styles with hair segments, which are either not subdivided or only subdivided in a small number. The developed SSALOD algorithm has its strength at close up views to render smooth hair, where a higher subdivision of hair segments is necessary.

8.1. Future Work

There are many areas were the hair rendering algorithm could still be improved. One part that was not implemented is shadowing of the hair. Here deep opacity maps could be implemented [Yuksel and Keyser 2008a]. From every light source first a depth map is rendered. Out of this depth map, opacity layers are generated. The depth map and the opacity layers are used for the final rendering of the hair. Deep opacity maps have the problem of two additional render passes per light source. This can lead to a performance problem when multiple lights are used.

Another feature, which has not been implemented was hair simulation. If hair simulation is integrated the SSALOD algorithm will need to be adapted for hair form dependent LOD calculations. The angle between hair segments is calculated once for the static hair guides. These angle calculations would need to be updated before every rendered frame. Making these calculations on the GPU should be reasonably fast.

Further performance optimizations could be done for the hair rendering algorithm. First, it needs to be evaluated if and how the L1 cache can be better utilized to increase performance. It could be evaluated if the use of OpenGL or Ogre has to do with the performance loss. For the future it could also be tested if future graphic APIs like AMD Mantle [AMD 2014] or DirectX 12 [McMullen 2014] have a positive effect on the performance of the developed hair rendering system.

The rendered hair count was 37632. For a more realistic hair style more hairs would need to be rendered. Up to 150000 rendered hair is the target. With improved graphic cards and further performance optimizations this targeted hair count should be possible.

Another area of improvement is artistic control of the hair. Especially, when the greater part of the hairs are generated, control for the hair style is limited. For our hair rendering system artists can control the basic shape of the hair style with guide hairs. In Frapper it is possible to modify the width of the hair, curly hair scale, random deviation scale and thinning scale to adjust the appearance of the hair. Translation form multi strand interpolation to single strand interpolation can also be influenced by the artist.

One problem that has not been solved is how to make partings. Separate hair parts would be the solution without changing the developed algorithm and also would the best solution for performance. Further research on how to give artist more controllability about the generated hair style is an important area for real-time hair rendering.

For hair shading only single hair scattering was implemented. For improved visual quality in hair rendering multiple scattering of the hair has to be taken into account. There has already been done research about multiple hair scattering in real-time by [Zinke et al. 2008]. Their GPU implementation is based on deep opacity maps and uses also a depth map for shaping the depth layers. The used data per layer is increased. For 4 layers 8 textures are needed to store the data. They achieved with their real-time dual scattering algorithm 14 frames per second. Not yet ready for real-time applications, but a step in the right direction.

In conclusion, it is possible today to render realistic hair on modern graphic cards and on current generation consoles like the Xbox One and PS4. The realism of real-time hair rendering can still be improved further for rendered hair count and visual quality.

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10. List of Figures

11. List of Tables

12. List of Abbreviations

2D	two-dimensional
ADHD	attention-deficit/hyperactivity disorder
AMD	Advanced Micro Devices
ASD	autism spectrum disorder
CPU	central processing unit
DFG	German research foundation
ELC	edge length constraint
FPS	frames per second
glsl	OpenGL shading language
GPAA	geometric post-process anti-aliasing
GPGPU	general purpose computing on graphics processing units
GPU	graphics processing unit
GSC	global shape constraint
ID	index
LOD	level of detail
LSC	local shape constraint
MSAA	multi sampled anti-aliasing
OIT	order independent transparency
OpenGL	open graphics library
PPLL	per-pixel linked list
R	primary highlight
SARA	stylized animations for research on autism
SSAA	super sampled anti-aliasing
SSALOD	screen space adaptive level of detail
TCS	tessellation control shader
TES	tessellation evaluation shader
TRT	secondary highlight
TT	rim light