

Implementation of volume rendering in C# for LightningChart

Alexey Tukalo

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<p>Abstract</p> <p>Arctive Oy is a Finnish software company based in Kuopio. Their main product is LightningChart, the fastest C# framework for the visualisation of scientific, engineering, trading and research data. The library contains a bunch of tools for visualisation of XY, 3D XYZ, smith and polar graphs, 3D pie/donut views, 3D objects.</p> <p>The company wanted to extend LightningChart's ability to render polygonal 3D models by volume rendering. It gives Arction an opportunity to attract new clients to use the product. As a result the framework will provide a unique possibility to render volume and polygonal models at the same visualisation.</p> <p>The project started from a literature research and comparison of different volume visualisation techniques. The best approach for the Arction's case was chosen and implemented it in the framework. The volume rendering engine is based on DirectX used together with C# via SharpDX API and HLSL shader language for low level optimisation of complex calculations.</p> <p>The final chapter of the report contains an evaluation of the results and suggestion for a future development of the engine.</p>			
<p>Keywords</p> <p>Visualisation, Ray Casting, 3D, C#, LightningChart, DirectX, HLSL, Image Processing, Volume Rendering, Rendering</p>			

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1 INTRODUCTION

This chapter contains brief information about the motivation behind volume rendering, my personal background in computer graphics especially volume rendering. It also introduces Arction as the owner of the project, explains the reasons for Arction's interest in the development, set requirements for the final product.

1.1 Motivation

Volume data is very common our day. An importance of the type of datasets will grow in the near future, because of development in the field of 3D data acquisition and possibilities to perform the visualisation of this type of information on a modern office workstation with an interactive frame rate.

Volume rendering is a process of multi-dimensional data visualisation into a two-dimensional image which gives the observer an opportunity to recognize meaningful insights in the original information. The technology allows us to represent 3 dimensions of the data via position in a 3D space and 3 more via color of the point.

The dataset can be captured by various numbers of technologies like: MRI¹, CT², PET³, USCT⁴ or echolocation. They also can be produced by physical simulations, for example fluid dynamics. The set of technologies mentioned before demonstrates that volumetric information plays a big role in medicine. It is used for an advanced cancer detection, visualization of aneurisms and treatment planning. This kind of rendering is also very useful for non-destructive material testing via computer tomography or ultrasound. Geoseismic researches produce huge three-dimensional datasets. Their visualisations are used in an oil exploration and planning of the deposit development.

1.2 Personal background

The first experience in the visualisation of volumetric data was gained by me during my internship at the Institute of Data Processing and Electronics, which belongs to the Karlsruhe Institute of Technology (KIT). I was a part of the 3D Ultrasound Computer Tomography (USCT) team there. Their main goal is the development of a new methodology for early breast cancer detection. An algorithm for visualisation of five-dimensional datasets was developed by me during

¹Magnetic resonance imaging

²Computer tomography

³Positron emission tomography

⁴Ultrasound computer tomography

the work placement. In result the it was integrated into Tomo Ray Caster 2⁵ and USCT's edition of DICOM Viewer.

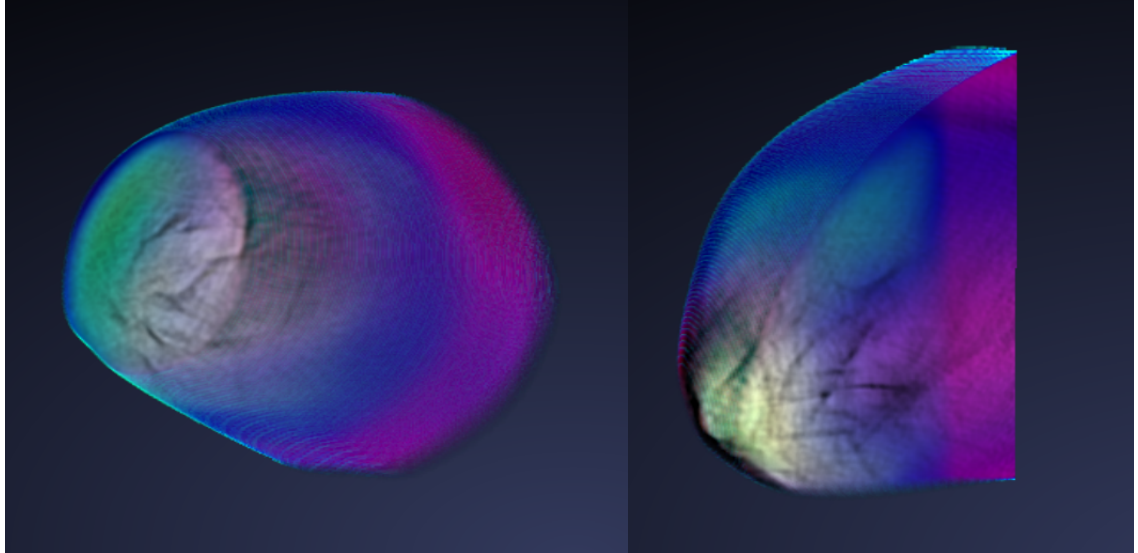


FIGURE 1.1: Volume visualisation of breast phantom made by USCT

The very first steps in modern computer graphics was made by me during the project. The first experience in work with WebGL was gained during customisation of the Tomo Ray Caster. GLSL as my first shader language was learned during the work. A lot of knowledge about image processing and scientific data visualisation, which became the basis for my thesis work was received by me at the workplacement.

1.3 Arction Oy and Ligthning Chart

Arction Oy is a Finnish software company based in Kuopio. Their team has a strong background in computer graphics and science. The main product of the company called LightningChart Ultimate. It is the fastest C# library for scientific and engineering data visualisation. The library is capable to draw massive XY, Polar, Smith and 3D XYZ graphs, polygonal mesh models, surfaces, 3D pies/donuts and Geographic information. The library has an API for .NET WinForm and WPF applications, it is also possible to use it for a traditional Win32 C++ software development. The main advantage of the library is the fact that it is based on low-level DirectX graphics routines developed by Arction, then the most part of competitors use graphics routines which belongs to System.Windows.Media.

⁵JavaScript framework for the visualisation of 3D data, developed in Institute of Data Processing and Electronics

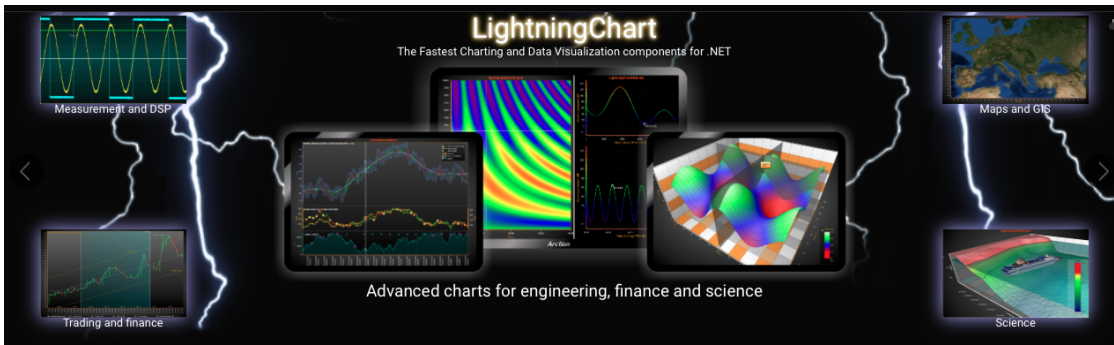


FIGURE 1.2: Example of LightningChart possibilities from the main page of Arction

1.4 Project Goals

So, as it can be concluded from the previous section, LightningChart is a very advanced software for 3D rendering based on polygons and lines. That's why, an idea to extend it by the special rendering engine for visualisation of volumetric data was suggested by me to the CEO of the company. It will give Arction's clients the unique possibility to combine visualisation of volume datasets with a wide range of other 3D possibilities provided by the library.

The rendering engine must be able:

- to render large multi-dimensional volumes with an interactive frame rate.
- to move and rotate the model in the chart's space.
- to provide clients with possibilities to apply windowing and thresholding to the initial dataset.
- to render the model semi-transparent.

Basically, this tool will give end users possibilities to change the contrast and brightness of the model's visualisation for better recognition of tiny details and make areas, which are out of certain range, totally transparent. It will also reveal insights into the internal structure of the model to the user via semi-transparency.

2 THEORY

This chapter explains the theory behind the project. It should introduce the main concepts of computer graphics, specify the difference between polygonal mesh model and volume rendering. It also contains an overview of different volume rendering techniques with their advantages and disadvantages in terms of speed, final image quality, flexibility and other implementation issues.

2.1 Rendering

Visualisation of 3D object as 2D image called rendering. Usually, 2D image is based on pixels¹. In case of a grayscale picture, it is a two-dimensional array and the value of the array elements represents the brightness of corresponding pixels on a screen. Configuration of colored images is dependent from a color model, the most popular one is RGB. It represents an image as three different grayscale pictures for three different colors called channels. In case of the RGB color model the images contain Red, Green and Blue values, sometimes it also keeps an informant about opacity and the channel called Alpha.

Color model is the mathematical abstraction which allows computers to calculate brightness of a corresponding point on the screen. RGB is the original one for modern computer graphics, because it represents colors in the way they are physically reproduced on screen. There are several other color models. They have their own advantages, for example, some of them gives us an advanced editing possibilities while others represent physical characteristic of different types of output devices like printers.

Multidimensional data can be represented in two different ways: as a surface and as volume. Future in this chapter, we are going to talk about these two concepts a little bit closer. We will highlight their advantage and disadvantages, common and uncommon features. Moreover, we are going to discuss an implementation detail of the techniques on modern hardware.

2.2 Polygonal Rendering

Today we are literally surrounded by the surface rendering based on polygonal mesh. The technology is used in computer games, design, cinema, science, engineering and etc. The technology is so popular that entire 3D graphic pipeline is built around the idea. That's why this type of visualization is easily accelerated by graphic cards.

¹a shortcut for picture element

2.2.1 Vertexts

Traditionally, 3D surfaces are constructed out of huge amount of polygons connected as a mesh. Due to simplicity, they usually have a triangular shape. It is possible to describe a triangle via list of three coordinates called vertices. The internal area of the shape filled with color during rasterization step. The color is calculated as dot product between the normal vector of the surface and the vector of light.

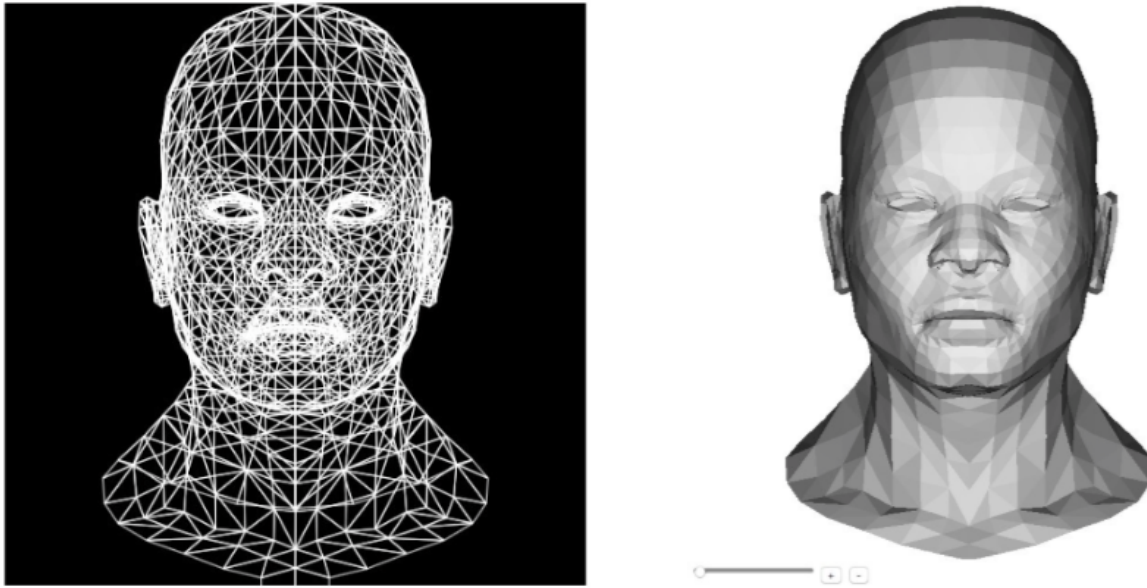


FIGURE 2.1: Wireframe and flat shading polygonal meshmodel

2.2.2 Normals

Surface normal vector of a triangle can be calculated as a cross product of two triangle's sides, but it will give an acceptable result only for very flat surfaces. That's why curve surfaces usually contain an additional normal vector for every vertex. They are able to significantly improve detailisation on the model. The information kept in them is used during shading and the tessellation of the model's geometry.

2.2.3 Textures

Very small details can be added to the model via textures. It is specific 2D image which is used to sample high frequency information during rendering. The picture usually contains local color values, but it also can carry any information about normal vectors for a nice visualisation of very small structures on the surface. Textures are mapped to the surface via third parameter of

vertex which is called texture coordinate. They keep any information about corresponding to this vector position in the 2D space of the image.

2.2.4 Redering process

Position, scale, rotation of the object and perspective characteristics of the space is specified via matrixes 4×4 . This kind of matrix allows to apply any kind of transformation possible in 3D space. Usually, three matrixes are applied to the object. The first one transfers an object to the world space coordinates, it specifies the position, rotation and scale of an original object in the world coordinate system. The next one is viewing matrix. It also takes in consideration position of camera and transforms the models to achieve desirable framing. The last matrix called projection. It applies perspective to the scene, in other word it defines an angle of view of the camera.

Specific program called shader receives all the information together with a camera and light source positions, after that they are able to perform calculations needed to render the final image in accord with the goals of the visualisation. Usually, the calculations are produced by graphic card in a parallel way.

2.3 Volume Rendering

Volume data are composed out of voxels². A voxel is simply a point in 3D space, which has a position and a color. Together gives us an opportunity to visualise up to six scalar parameters. There are two ways to render volumes. We are going to discuss about main principles, advantages and disadvantages of the technologies in this section.

2.3.1 Indirect

The first one called indirect volume rendering. It is based on the idea that it is possible to extract surface out of the dataset during preprocessing and render the surface as a polygonal mesh. Several algorithms are invented for this application:

- Marching Cubes
- Surface Tracking
- Fourier Transfor Rendering

It is the oldest idea behind volume rendering and it has plenty of disadvantages:

- complex and slow preprocessing algorithms

²volume element

- can be inaccurate due to noise
- sometimes does not able to generate an isosurface out of specific dataset, for example smoke
- lose an information about an internal structure
- need to repeat preprocessing to apply changes in a transfer function

But the algorithm is very popular for generation of medical illustrations, video or other static visualisation. The main advantage of the solution is that nicely preprocessed model can be easily rendered via well-known technique for 3D mesh model's rendering. They can be used even in very weak hardware.

Unfortunately, this technology is not suitable for our project, because it does not satisfy our requirements. First of all it is not acceptable for us to lose an internal structure and lose an opportunity to modify the transfer function runtime.

2.3.2 Direct

Direct volume rendering does not require any preprocessing. The data are visualised from an original dataset. It gives the algorithms an opportunity to modify a transfer function runtime. There are four most common technique for direct volume rendering algorithm, which will be discussed more detailed in this section in the future.

For an implementation of hardware acceleration for rendering process a volume data has to be loaded to the graphics cards. It is usually served as 3D texture or as set of 2D textures. For the optimization of a texture's buffer consumption, several slices can be collected to one huge texture map.

Texture-based

As it was mentioned before the graphics pipeline of modern graphic cards is optimized for rendering of polygonal mesh models. So, volume rendering algorithms are forced to use this set of tools to achieve hardware acceleration. Texture-based volume rendering is the most straightforward way to achieve the aim.

As it was already said textures are used to add tiny details to polygonal models. Any graphic library has an advanced set of tools for texture mapping, which can be used to this kind of volume rendering. The algorithm creates set of planes called proxy geometry. Transfer function maps the volumetric dataset on the proxy geometry. The final image is constructed out of the planes with mapped on them textures via Alpha-blending.

A proxy geometry can be created in two different ways. The first one called 2D texture-based rendering. In this case three different sets of planes are generated. All sets are generated perpendicular to a different direction in 3D space. This approach leads us to sudden jumps in image

quality for different camera position and does not allow to change the sampling rate of the visualisation.

That's why the second way was invented. It is called 3D texture-based volume rendering. In

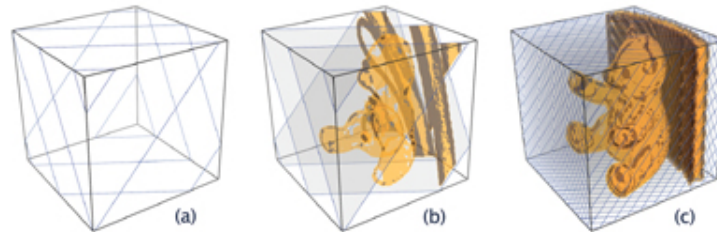


FIGURE 2.2: a) example of proxy geometry for 3D texture-based volume rendering a) Texture-based volume rendering with a lower sampling rate c) high sampling rate texture-based volume rendering

this solution the algorithm creates only one set of planes which are always perpendicular to the camera and textures are mapped on them differently for the different camera position.

It gets rid of an artifact of the first technique and allows to modify the sampling rate of the visualisation. The approach is the most popular direct volume rendering algorithm among medical software. But it has significant disadvantages against competitors. It is able to use, transfer function to emphasize or classify features of interest in the volume, while final blending is performed via Alpha-blending provided by DirectX API. It makes the approach less flexible than all other methods which provides more advanced tools for blending of sampled information.

Ray Casting

An image is produced by the algorithm throughout sampling of the volume along tracks of the rays which travel inside the dataset. A simple realisation of hardware acceleration of the approach require generation of boundaries for our volume. Usually they are represented by a cube.

Volume Ray Casting includes four simple steps:

- An engine shoots a ray in a direction of observation for every point on a screen.
- The ray travels through a scene and dataset.
- A vector of the ray's track is calculated based on the position where the ray hits front and back faces of the cube.
- The volume is downsampled along the ray track and color of the pixel is calculated out of collecting information in accordance with a Ray Function.

Ray Function is a core of the algorithm. Such a high level of flexibility is provided to the algorithm by the feature. It possesses an entire power of the technique, because it specifies the

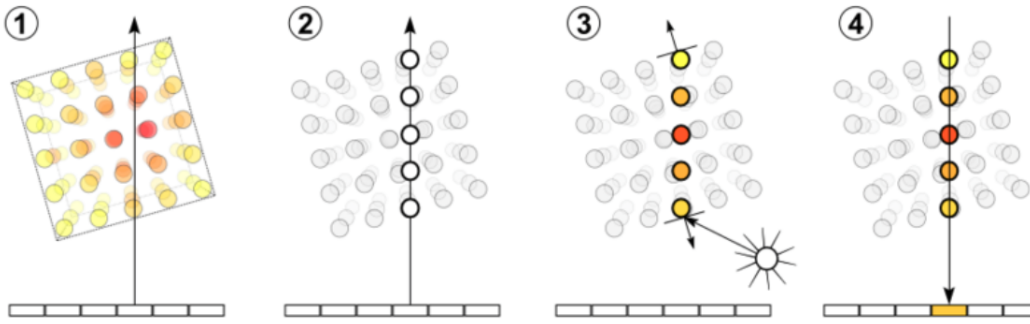


FIGURE 2.3: Ray Casting steps: 1) The ray is shot, 2) The ray travels through a scene and dataset. 3) Inlet and outlet position of the ray's track are detected 4) downsampling and the pixel's color calculation process

way how the data is combined. It is very powerful tool for feature extraction, because it controls how color, opacity and gradient of isosurface are calculated by the engine. Transfer function and classification are also performed via Ray Function.

The algorithm has very high rendering quality without any additional artifacts. Due to the reason that every ray is calculated separately it is usually implemented in modern hardware focused on parallel calculations. The main problem of the algorithm is that rays usually do not hit the voxel's centers. In case of 3D space an interpolation is a very complex operation in terms of calculational expenses, which has to be performed to get a nice sampling.

Splatting

The technique was created to reduce interpolation expensis which were the main problem of Volume Ray Casting. The solution uses totally oposite aproach to reach the goal. Instead of sampling of the dataset by ray, the algorithmm projects the voxel to the image plane one by one. Of course the voxel porjections do not always fit excatly to pixels' grid of screen, but the problem is again solved by an interpolation, fortunately in this case the operation is much less expensive in term of calculation, because it is perfomed in 2D space.

The final pixel's color is calculated in a very similar way used by Ray Function, that is why the algorithm is as flexible as Volume Ray Casting. The main disadvantage of the approach is that some artifacts have contributed to the final image due to boxes overlap. It is also difficult to change the sampling rate of the approach. The issues make the algorithm less interesting for us.

Shear-warp

As Splatting, the approach also tries to accelerate Ray Caster by solving of the interpolation issue, but it uses totally different way to illuminate the problem. Shear-warp has a very similar idea to the Volume Ray Casting. In some sense it is an optimization of the technique which

makes rays always hit exactly in the center of the voxel.

The aim is achieved by the transformation of the volume data to sheared object space by translation and scaling of slices. After that an intermediate 2D image is produced by Ray Casting performed in the shared object space. The transformation brings some distortion to the output image. It is fixed at the last step of the algorithm called wrapping. The final image is the result of the transformation applied to the intermediate picture.

This solution gives us the fastest volume rendering process, but unfortunately the algorithm also

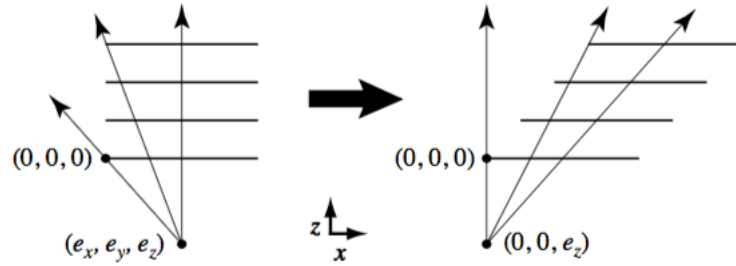


FIGURE 2.4: (left)Ray Casting in world coorinates, (right)Ray Casting in shear object coordinates

suffers from several types of artifacts. Some of them are caused by an unevenness of sampling rate along different directions, others are produced by 2D transformation on wrapping stage.

3 IMPLEMENTATION

This chapter contains detailed explanation of the product implementation. It describes how the engine works, what kind of parts contains and which tools are used in it. The key step of the engine work is highlighted and explained in this chapter.

In accord with results of literature research, several the most common algorithms for volume rendering were compared and the most suitable approach was implemented as Volume Rendering Add-On of LightningChart Ultimate. One of the main requirements for the LightningChart's volume rendering engine is possible to combine volume and other 3D visualisation at the same chart space. Easy and accurate conversion between volume's and chart's coordinate systems is needed for this purpose. Only volume ray caster and texture-based volume rendering can provide us with the feature. The algorithms keep entire visualisation inside the coordinate system of a proxy geometry. It is placed on the coordinate system of the chart. It means that the coordinates of volume model can be easily converted to the coordinates of the entire chart. Shear-warp and Splatting do not use any kind of proxy geometry, that is why they are not good solution for Arction's case.

Another important thing is implementation of rotation, scaling and transmission of the model in the chart space. As it was already mentioned the proxy geometry also makes it much easier. But this approach is not fully applicable for 3D Texture-based solution. In this approach slices always have to be perpendicular to the camera, that is why rotation has to be implemented in the process of texture mapping.

Finally, there are only two technologies. The final choice is Ray Casting, because it has better image quality than 2D Texture-based rendering. In addition, Texture-based volume rendering is less flexible than Volume Ray Casting.

3.1 Tools

This part of the chapter describes technologies used in the implementation of the project. It also gives a short explanation to their usage in the solution. The rendering engine has to become a part of LightningChart Ultimate. An integration with the library gives some restrictions in terms of set of tools which can be used in the project and it plays a key role in technology selection.

3.1.1 C# and .NET

C# is general purpose multi-paradigm programming language with strong types. It is created by Microsoft as native language of .NET Framework. Our days the language can be used for Web services, Windows desk-top and mobile applications, computer games with several different

game engines. In addition, Xamarin created set of tools for cross-platform C# development.

In some sense it contains constructions inspired by an object-oriented, imperative, functional and many other programming paradigm. The language belongs to C-like family, that is why the curly-brace syntax looks very similar to the C, C++, Java. C# combines an advantages of Java and C++ in single powerful and elegant way. It is more simple and safe than C++, but at the same times it has advanced features like: pointers arithmetics, enumerations, lambda expressions, structs, delegates and implicitly typed local variables. Even today when the most part of them are implemented in the last version of Java, C# still is way more flexible.

Other advanced feature of C# is Language-Integrated Query expressions or shortly LINQ, it is set of functions for strong-typed queries, which allows to write very short functional styled code for collection processing.

.NET Framework contains applications run in virtual execution system called the Common Language Runtime shortly CLR and more than 4000 of class which implements wide range of useful functionalities. The runtime is able to execute an Intermediate Language, which is compiled from C# or 20 other languages.

C# is used in the project for as close as it is possible integration with LightningChart Ultimate. It performs loading and preprocessing of the dataset and management of visualisation process.

3.1.2 DirectX 11

DirectX is a C/C++ API¹ for work with multimedia resources created by Microsoft for Windows and Xbox. It contains advanced tools for rendering of 2D and 3D graphic and sound management. Direct3D is a part of the library responsible for hardware accelerated rendering of 3D graphics. The tool is mainly focused on GPU accelerated rendering of polygonal meshmodels.

Rendering Pipeline

Key concept of the library is rendering pipeline. It is a very general term in computer graphics. The pipeline is a sequence of stages which receives an input data as set of polygons, textures and variables, process the information step by step and generates the final image in the end.

Direct3D's pipeline has two types of steps:

- Fixed-function - perform certain processing operation which can be customized due to some level through the API.
- Programmable - processing is performed by so called shader program. It is function which is created by developer and satisfies input and output parameters of the stage.

¹ Application Programming Interface

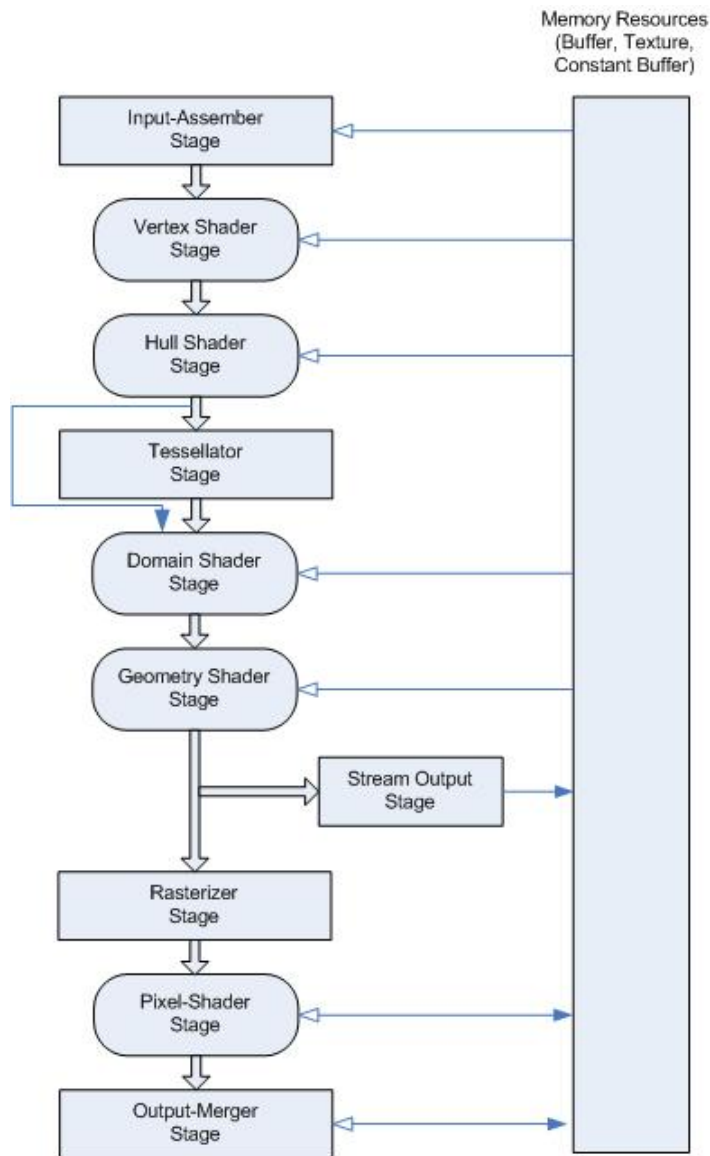


FIGURE 3.1: Flowchart of Direct3D 11 Graphics Pipeline

The graphics pipeline is shown on Figure 3.1. Boxes with rounded angles represent programable stages and other ones are fixed-functions. Let me explain every step of the pipeline more detailed:

- Input-Assembler Stage receive input information as set of buffers and supply future to the pipeline. There are four types of buffers in Direct3D:
 - Vertex Buffer is used to define geometry of the object by list of vertexs. Every vertex has to follow Input Layout deffined for the pipeline by developer. It discribes

the vertex members like: position and texture coordinates, color value, normal etc used in this application.

- Index Buffer contains an order of vertices as sequence of integer variables.
- Constant supplies pipeline with a constant data, like transform matrixes, position and directions of light sources, textures, and so on.
- Vertex-Shader Stage is the first programmable stage of the pipeline. Vertices are read one by one and processed in accordance with Vertex Shader program supplied by developer. For best performance the processing has to include every operation which can be performed on every vertex individually. The function is not able to destroy or create new vertex.
- Hull Shader, Tessellator and Domain Shader stage are used together to archive tessellation² of the mesh.
 - Hull Shader program includes two functions. The first one receives primitives and calculates tessellation factors out of the data. The second function is called once for every control point and creates them.
 - Tessellator uses data provided by Hull Shader and one of several algorithms to choose the best point to break of current primitive into smaller polygons.
 - Domain Shader uses an original information from Hull Shader together with results of tessellator to generate new vertices list.
- Geometry Shader receives several vertices at the same times and perform operations on them. An ability to add and remove points from pipeline makes the function extremely powerful and flexible tool. For example it can easily turn single vertex to the polygon of even set of polygons. It is able to pass geometry further along pipeline or away to output stream.
- Rasterization projects geometry to the final image and determines which pixels are covered by the polygons. It interpolates the vertices' attributes inside the primitives to get the pixels values for the area. It also performs depth and stencil tests.
- Pixel shader is executed once for every pixel on the output target. It is supplied with an information from Rasterization step and calculates per pixel data for example color of image's points. Usually texture sampling and high quality lighting calculations are implemented by pixel shaders.
- Output-Merge Stage uses pixel shader's output together with depth/stencil information to generate final image and write it in appropriate way to render target.

It is worth to mention that a render target is not always represented by screen. Sometimes the output is stored in texture. For example the image can be loaded again to graphic card and sampled to get some precalculated previously information. The technique called multi-pass rendering.

²Process of mesh model's enhancement via automatic generation of additional polygons

HLSL

There are two way of rendering pipeline customization. Fixed-functions behavoure can be modified by the API and programable stages flexiblities is orgonised via special type of programming languages called Shader Languages. Direct3D's realisation of shader language called HLSL³.

The language is basically significantly modified version of C. The lanaguage does not support features like pointer artichmetics and dynamic momory allocation, but the syntax is still understandable for C developers. It extends C syntax by classes, several new data types, buffers, sematics and huge library of useful for shader development functions. There are vector, matrix and 1D-3D texture data types which are very useful for processing of 3D primitives. As it was already mentioned buffers are used to supply pipeline with data. Sematics contains meta-data which is related with data exchange among fixed-function and programable stages of the pipeline.

3.1.3 SharpDX

As it was already mentioned DirectX is C++ library, so it is not possible to use in directly from C#. The problem is solved by SharpDX. It is open-source managed C# wrapper for an original API of DirectX. It plays role of bridge between API and .NET. As result developers are able to manipulate the functionality of the API from C#.

Every feature of the API is implemented in a very natural way. That is why a huge amount of tutorials and example avable for original C++ API can be easlyly translatted to C# and SharpDX. Even original documentaion is still useable for SharpDX development.

3.1.4 LightningChart Ultimate

LightningChart Ultimate is the fastest C# library for scientific and engineering data visualisation. It is able to draw massive XY, Polar, Smith and 3D XYZ graphs, polygonal mesh models, surfaces, 3D pies/donuts and Geographic information.

The library has an API for .NET WinForm and WPF applications, it is also possible to use it for a traditional Win32 C++ software development. The main advantage of the library is the fact that it is based on low-level DirectX graphics routines developed by Arction, then the most part of competitors use graphics routines which belongs to System.Windows.Media.

An intergration with LightningChart has sevral advantages and disadvantages. In one hand, it applies main role in terms of tools selection for project implementation, because deep enough integration can be achived only via usage of exactly same set of technologies. It also forces the volume rendering engine to follow similar class arcitecture. Moreover, LightningChart is commercial software package. That is why any external dependences have to be avoided as much as it is possible. It means that even open-source libraries can not be used without extrimly important reason.

³High Level Shader Language



FIGURE 3.2: Some of LightningChart Examples

On the another hand an abilities of LightningChart to draw 3D polygonal mesh models make the development much more simple. The library is able to rotate, scale and move the models around chart's space, so the functionality can be easily applied to proxy geometry. As result the features are implemented without almost any development from the side of volume rendering engine. In addition it is a huge advantage for clients, because volume and mesh 3D models can be visulised at the same chart in the same coordinate system. It provides them with really unique and powerful opportunity for complex 3D visualisations.

3.2 Visualisation process

This section of the paper explaines main principles and implementation detailes of the project. It disribes the main challangs and explain how were solved during development of the rendering engine.

3.2.1 Loading and preprocessing of dataset

The most commune way of volume data distribution is collection of 2D slices. The 2D slices are just images in common format. Sometimes they can be represented as set of DICOM⁴ files. In this case they contain metadata of the studies toughere with embeded picture. Volumes can also be distibuted as table of original values. The table usually is part of RAW file which also contain some meta information. Actually, RAW is several different format with commone name and more detialed specification of every single approach depends from machine which perfomed the data aquisition.

Unfortunately, current implementation of the volume rendering engine supports only first ap-

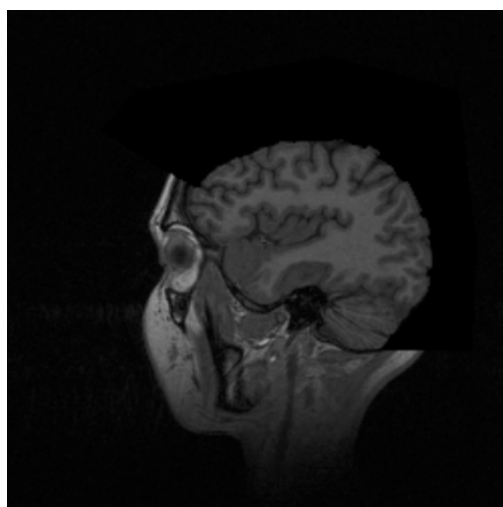


FIGURE 3.3: Single slice from Volume dataset.

proach, because slice-based data is easier to get. Specific software can converte DICOM slices to the picture formats supported by .NET like *.JPEG, *.TIFF and *.PNG. RAW volume data files can be converted to *.CSV files, but due to the reason that there are many different specifi-cations of the files it is very difficalt fo find the software.

.NET tools for file handling load images in supported by framework formats. The slices are loaded to the memory from specified folder as an array of bitmaps in the same order they are already stored. An example of slice is shown on Fugire . DirectX 11 also supports 3D textures, but the approch was not used in the engine, becuae the feature is not supported by DirectX 9. Arction wanted to have an opportunity to port the volume engine to DirectX 9 quickly, if it would be needed.

Texture buffers have a limmited amount of avaiable slot. Slices usually have a very low resolution so it is not efficent to load them one by one, due to an optimization of texture buffers' consump-tion an array of slices is mapped to the big texture map. The map contains slices mapped from

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FIGURE 3.4: An example of slice map

left to right in according with an array index, look Figure . A bitmap processing is accelerated via pointer arithmetic, but any way it requires some time. That is why the engine is also able to load preprocessed texture map for quicker start of visualisation.

TABLE 3.1: Characterisation of different technologies

Feature level	Maximal size of texture map
9_2	2048
9_3	4096
10_0	8192
10_1	8192
11_0	16384
11_1	16384
12_0	16384

DirectX has a limitation in terms of the biggest available texture size, which can be loaded to the graphic card. The value depends from feature level of the graphic card, look table 3.1. Feature level defines the functionality supported by the graphic card. Usually, modern graphic cards have at least 11_0. It means that they support up to 16 384 pixels per side. Such a big texture can keep volume dataset with more than 600 voxel long in every dimension. It is possible to render even bigger models, because several texture maps can be generated if it is not possible to fit entire data into single one.

3.2.2 Multi-pass rendering

Possibility to render scene in several steps makes rendering pipeline especially flexible. The technique called Multi-pass rendering. Sometimes it is more efficient to render scene in several steps. Multi-pass rendering is based on an idea that every step except the last one outputs the result of performed calculation to texture. The final pass sample information from the set of textures and generates the final image.

Deferred rendering is one of the most popular realisation of the idea. The technology is created for rendering of scenes with large amount of dynamic lights. Traditionally this kind of functionality requires a complex set of shaders. Multi-pass approach breaks the process to smaller pieces and performs the calculations separately for every step. It allows to simplify an architecture of rendering framework. It can also give an opportunity to apply GPU acceleration to some parts of rendering algorithm which used to be executed on CPU before.

Our volume ray caster is also going to get some advantages from multi-pass rendering. In case of the solution it has only two passes and it allows the algorithm to determine vectors of the sampling ray in the volume coordinate system without any additional mathematical calculations. It means that entire rendering pipeline of the engine contains two typical rendering pipelines. The first one generates texture which contains an important information for rendering of final image at the second pass. Both passes use only vertex and pixel shader programs.

3.2.3 First pass

At this step rendering engine has to generate texture which keeps an information about the exit position of sampling rays. For this reason front-face culling mode of Direct3D has to be turned on. It makes the library to draw only polygons which are normally not visualised, because their front side looks in an opposite to the screen's direction.

An input of the first pass contains only set of vertices for boundaries of the dataset, constant buffers for slice range clipping and matrices for calculation of the vertices position of the chart space. The boundaries are always represented by cube. The cube contains 8 vertices calculated on C# according with required size of the volume model. Constant buffer is represented by two Vector3 variables, one of them contains the number of minimal slice for every direction and another one keeps an information about maximal boundaries. We also have three traditional for 3D graphic Matrices: World Coordinate, View, and Projection. These matrices have unique values for every object and allows to calculate desirable position, scale and rotation of the object in screen coordinates.

The Vertex Shader of the first pass calculates positions of the cube vertices in accordance with clipping range buffers. After that matrices are applied to transform the geometry to the screen coordinates. Internal coordinates of the dataset are calculated out an original position of vertices. They are represented by Vector3, with value range from 0 to 1 along every axis and stored as texture coordinates.

The Pixel Shader represents the coordinates as color. X coordinate is stored in red channel, Y one is stored in green channel and Z coordinates is stored as blue value. The final result of the first pass is demonstrated on Figure 3.5.

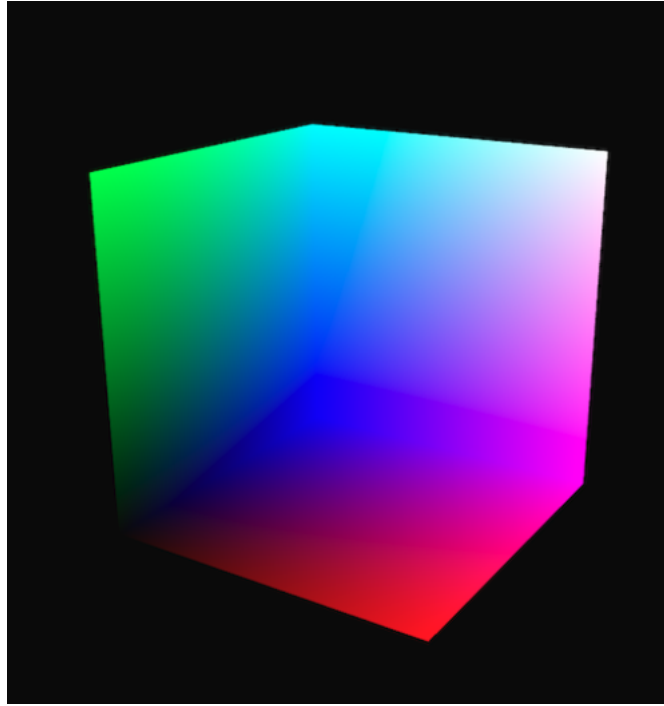


FIGURE 3.5: First pass output

3.2.4 Second pass

At this pass the engine has to calculate vector of sampling ray displacement through dataset. The enter coordinates of the rays are needed for the calculation that is why default culling mode has to be restored. The input of the pipeline has a set of vertices, matrices, an original dataset represented as texture map, texture rendered at the first pass, buffers with slice range, contrast, brightness and thresholds setting.

Second pass has exactly same vertex shader with the first one, but due to changes in culling mode it outputs enter point of sampling rays. In other words the coordinates of the points where the rays hit the boundaries. Figure 3.6 shows them at the same way it was done on the first pass.

The pixel shader samples coordinates where rays hit the back side of cube from the texture generated at the first pass. After that it subtracts enter coordinates calculated at the vertex shader of the second pass from the information. The operation result is the vector of the rays track. The tracks are visualized as colors on the figure 3.7. The vector is divided by sampling rate to get step

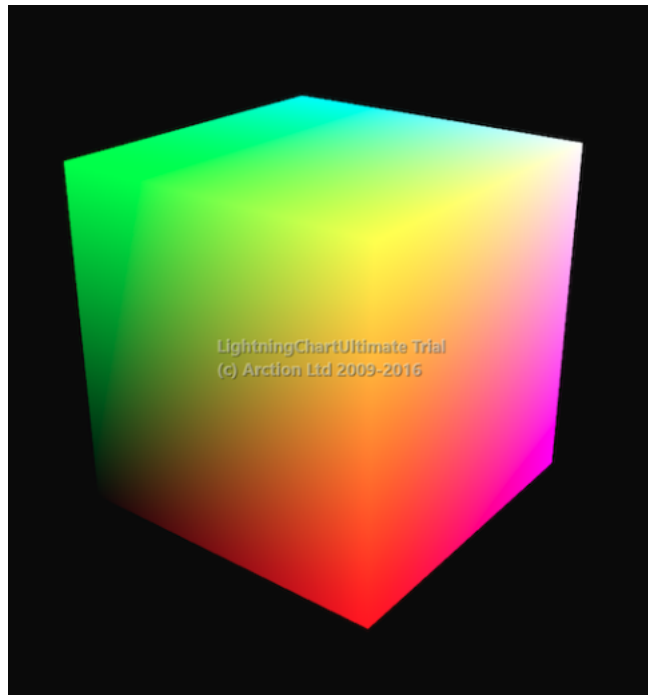


FIGURE 3.6: Coordinates of the hit points.

vector. Actual volume sampling is performed by for loop. It starts from the hit point of the ray and adds a step vector every iteration to get coordinates of new sampling point. The data is sampled out of volume by function which calculates correspondent position on the texture map.

It calculates the nearest slice correspondent to the Z position. After that it checks how many full rows are included in to the value and what is the column number of the rest. Values from two closest slices can be interpolated to get smoother result. Handling of the information depends from Ray Function.

Empty space skipping

The most part of volume dataset is represented by an empty space. Empty space does not contain any important information, usually it is represented by pixel with a very low value per each channel. In our case a voxel is classified as empty one if its values are out of a threshold range for all of its channels. There are huge amount of rays which travel through arrays which contain only empty space. The optimization has to prevent high resolution downsampling of the regions.

Due to realization of the technique, the sampling is broken down into two steps. At the first step ray travels through dataset with a very low sampling rate. It saves positions of the first and the last non-empty voxel hit by the ray. After another ray goes through the dataset with a higher

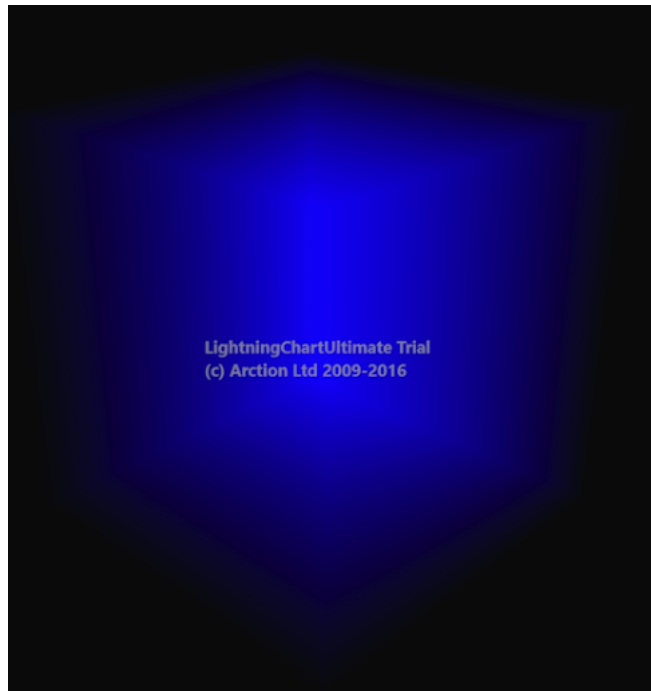


FIGURE 3.7: The visualisation of sampling ray vectors' tracks

sampling rate. The second ray starts one low resolution sampling rate step vector earlier than the position of the first non-empty voxel. It stops one low resolution sampling rate step vector after the last non-empty voxel detected by the first ray. The process is shown on figure 3.8.

High and low resolution sampling rates are specified by constant buffers. High sampling rate determines rendering quality. An optimal quality is reached then it matches an amount of voxels in the longest dimension, because it allows to perform uniform sampling of entire dataset and collect all information stored inside. Low resolution sampling can only be defined via experiment. Too small low resolution sampling rate can contribute some artifact to the final visualization. It is a trade of quality and frame rate. The right value has to keep an interactive framerate and unnoticeable artifacts.

Ray function

Ray function determines how the sampled data is combined. Different ray functions allow to extract different features out of the dataset. Two most common ray functions are implemented in our rendering engine.

Accumulation function uses alpha-compositing to get composed as much data as it is possible. The visualizations produced by the technique look like semi-transparent gel. Ray function implementation is represented by a for loop, which runs from 0 to the value sampling rate. Every iteration contains several steps:

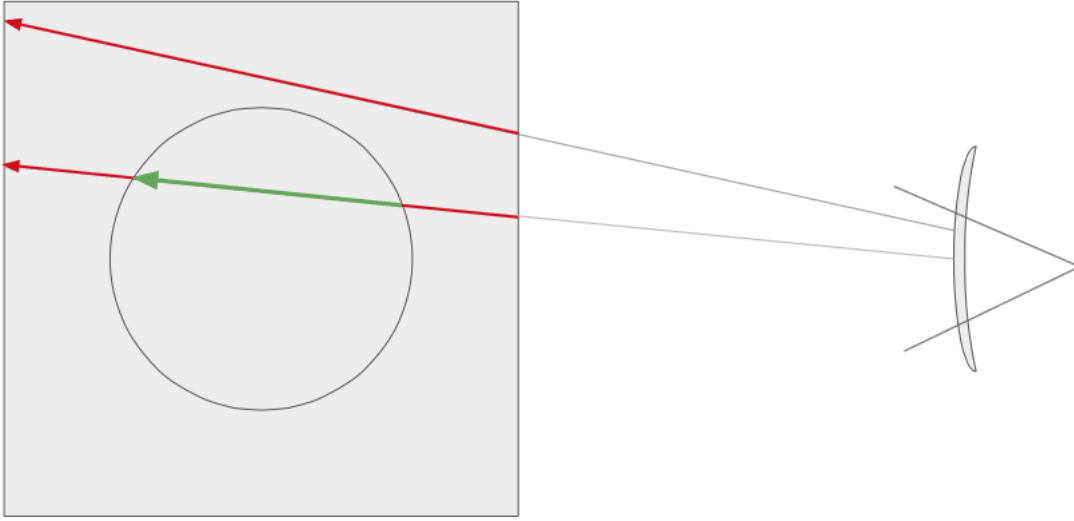


FIGURE 3.8: Red arrows represents low resolution sampling rate ray. Green demonstrates high resolution sampling one.

- The voxel is sampled out of texture map.
- The voxel's value validation is performed by if-statement. It checks that every channel is in its personal threshold range. If the voxel is empty next four steps have to be skipped.
- The alpha is calculated in according with an equation:

$$\alpha_{output} = \alpha \times opacity \times \frac{1}{sampling\ rate} \quad (3.1)$$

- The colors are calculated in according with an equation:

$$color_{output} = (1 - \alpha_{accumulation}) \times (color + brightness) \times contrast \times \alpha \quad (3.2)$$

$\alpha_{accumulation}$ contains previously accumulated alpha values. Brightness and contrast are supplied by constant buffers and used to perform windowing.

- After that the colors and alpha are added to the correspondent variable which keeps a previousl accumulated infomation.
- If-statement checks that alpha is not oversaturated. The ray has to be terminated in this case.
- Step vector is added to reach next sampling position.

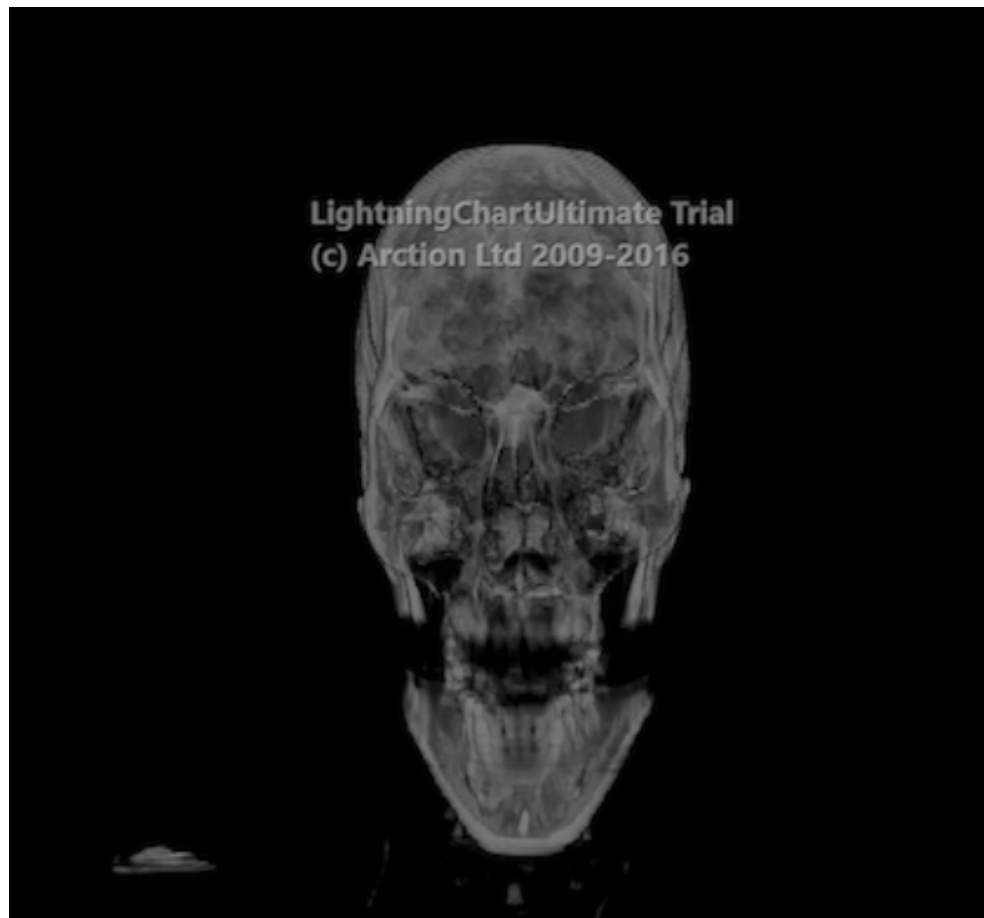


FIGURE 3.9: An example of an accumulation function output

An example of images produced by an accumulation function is demonstrated on figure 3.9.

Maximal intensity visualise only the brightest value sampled by ray. It gives very similar result to the X-ray images. The ray function is very similar to the previous one. It also use for loop and step vector to sample the dataset, but it does not accumulate the information as it is done in previous example. Instead it keeps the biggest value which ray meet during the travel and put it to the pixel in the end. It allows end user to identify specific structures inside the volume. An example of the ray function result is shown in the figure 3.10

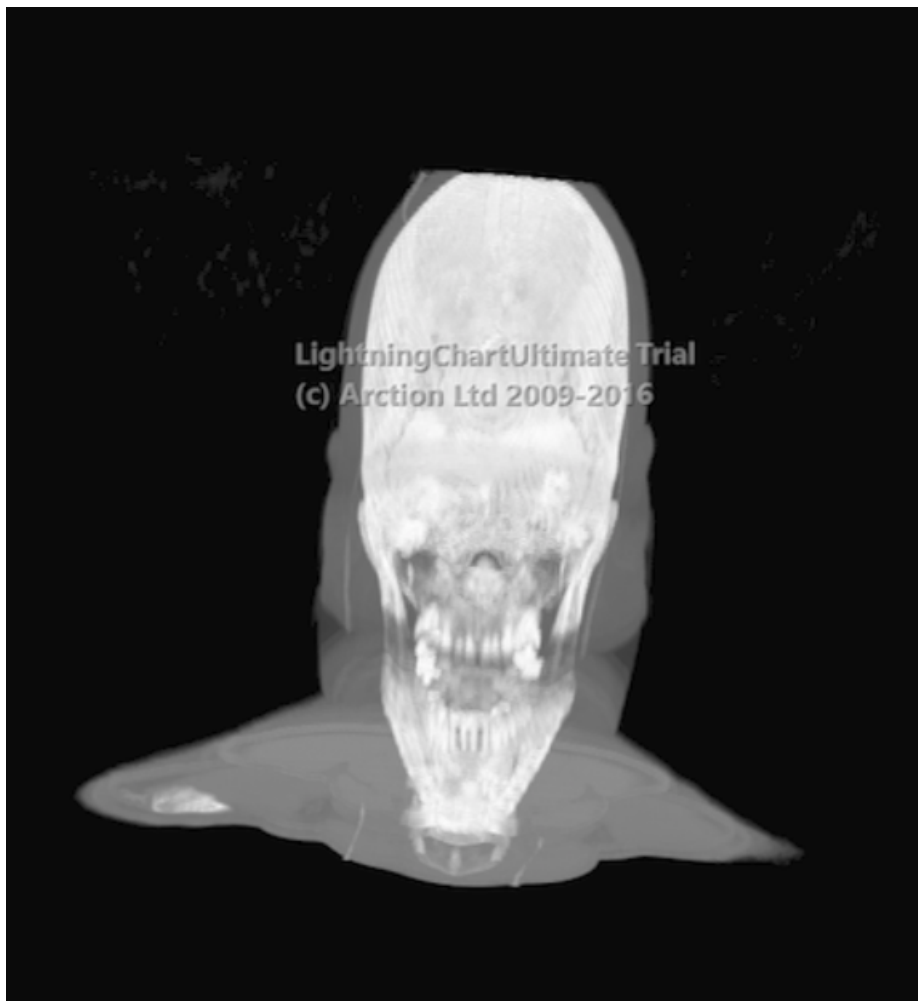


FIGURE 3.10: An example of maximum intensity function output

4 Conclusion

4.1 Results

4.1.1 Rotation and position

4.1.2 Settings

Windowing

Thresholding

Slice range clipping

4.1.3 Mouse picking

4.2 Discussion

4.3 Future Development

5 REFERENCES

6 Appendix