INTERACTIVE DESIGN AND DEBUGGING OF GPU-BASED VOLUME VISUALIZATIONS

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Abstract: There is a growing need for custom visualization applications to deal with the rising amounts of volume data to be analyzed in fields like medicine, seismology, and meteorology. Visual programming techniques have been used in visualization and other fields to analyze and visualize data in an intuitive manner. However, this additional step of abstraction often results in a performance penalty during the actual rendering. In order to prevent this impact, a careful modularization of the required processing steps is necessary, which provides flexibility and good performance at the same time. In this paper, we will describe the technical foundations as well as the possible applications of such a modularization for GPU-based volume raycasting, which can be considered the state-of-the-art technique for interactive volume rendering. Based on the proposed modularization on a functional level, we will show how to integrate GPU-based volume ray-casting in a visual programming environment in such a way that a high degree of flexibility is achieved without any performance impact.

1 INTRODUCTION

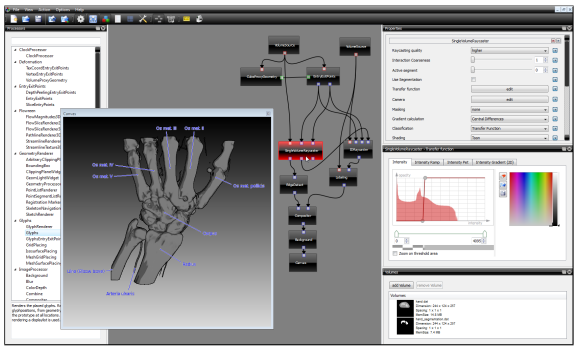
In many domains the amount of volume data is rising due to new or refined sensing and simulation technologies and the more widespread use of data acquisition techniques. For example, well established imaging techniques such as computed tomography (CT) and magnetic resonance imaging (MRI) and more recent functional imaging techniques like positron emission tomography (PET) are increasingly used in daily medical routine. In addition, due to the omnipresence of volume data and the increasing familiarity with these data the problems posed and the questions asked by the users become more and more complex.

To answer such a question often new visualization techniques need to be designed. Many modern volume visualizations employ GPU-based raycasting (Krüger and Westermann, 2003), which can be considered the state-of-the-art technique for rendering volumetric data. Its main advantages are the high flexibility and the achieved image quality. By utilizing modern graphics processing units (GPUs) for all computations performed during the ray traversal, interactive frame rates are achievable even when applying quite complex effects. However, graphics programming and especially GPU programming is complex, error-prone, and time-consuming.

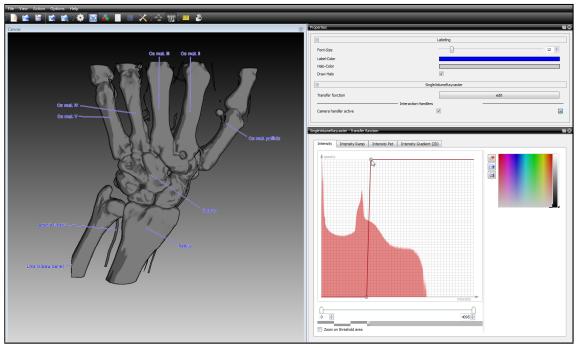
Applications intended for the design of new visualization techniques often use visual programming paradigms in order to manage the described complexity. The rendering process is decomposed into functional components which can be flexibly arranged in data flow networks. Since usually this decomposition is done on a rather high level, the resulting entities are quite complex, e. g., a component which performs a complete GPU-based volume raycasting. This level of abstraction results in rather general components, which consequently leads to reduced performance.

In this paper, we present a careful modularization of the GPU-based volume raycasting process and its realization on current graphics hardware. By decomposing the raycaster itself into small-grained functional components (called *processors*), we are able to exploit the visual programming paradigm on a lower level and are thus able to achieve unbiased rendering

performance. By introducing the visual programming concept to low-level GPU-rendering, we are able to transparently interweave it with the visual programming concepts used on a higher level, e. g., for application prototyping. Thus, complex visualization applications can be generated exploiting a single pervasive visual programming paradigm, which gives full control on the application level as well as the GPU level. The latter is essential in order to generate applications, which can visualize today's data sets at interactive frame rates. To further support the rapid development of such applications, we introduce visual debugging functionality, which gives access to intermediate results otherwise not accessible in the final application. All the described concepts are available as open source within the Voreen[1] volume rendering engine (Meyer-Spradow et al., 2009). Within this framework, new visualization applications can be generated in the *development mode*, in which the user has full access to all available processors, the underlying data flow network as well as a preview visualization (see Figure 1 (a)). To test these applications, the *visualization mode* can be used, which gives only access to the user interface components specified by the application developer (see Figure 1 (b)). In the remainder of this paper, we will describe the proposed modularization of the GPU-based volume raycasting and demonstrate the implications on the application development.



(a) development mode



(b) visualization mode

Figure 1: Visual programming is possible on multiple levels of abstraction: in the *development mode*, the user can modify the data flow network and choose, which properties are editable in the *visualization mode*. In the *visualization mode* only these properties are shown while the data flow network is hidden.

2 RELATED WORK

The analysis and visualization of volume data has become a frequent task for scientists, and therefore many libraries, applications, and rapid prototyping environments (RPEs) are available. Since the use of libraries requires extensive programming skills and applications are limited to built-in tasks, RPEs are very popular. They often use visual programming (Johnston et al., 2004) to let the user graphically combine objects in order to achieve the desired goals. All concepts described in this paper are realized within the Voreen volume rendering engine (Meyer-Spradow et al., 2009), which is freely available.

The established RPEs like Amira (Stalling et al., 2005), AVS/Express (Hewitt et al., 2005), MevisLab (Rexilius et al., 2006), SCIRun (Weinstein et al., 2005), and VisTrails (Bavoil et al., 2005) focus on the entire process of analyzing data; the visualization is only the final step and in some systems even a minor aspect. Mostly slice-based methods are used for the visualization of volumetric data which have algorithm-immanent disadvantages such as less flexibility and worse image quality in comparison to raycasting. MevisLab also provides a GPU-based raycasting block which supports reconfiguration of the renderer on a per-object basis (Link et al., 2006), but it does not allow to decompose the raycaster. Furthermore, the relatively new open source RPE XIP (Prior et al., 2007) also uses only slicing for volumetric rendering. Overviews and comparisons of some of these packages are given in (Hahn et al., 2003; Bitter et al., 2007). Caban et al. compared several open-source libraries and applications in (Caban et al., 2007). Botha presented an RPE in his PhD thesis (Botha, 2005); a special feature is the hybrid scheduling approach which supports event-driven as well as demand-driven scheduling (Botha and Post, 2008). It uses the VTK library for visualization which supports slicing only.

A rendering framework for using different

[1] www.voreen.org

GPU-based raycasting techniques is presented in (Stegmaier et al., 2005), it provides some basic functionality and achieves its flexibility by replacing the shaders. Since raycasting is not split into subtasks, the advantage of combining small blocks is missing. Rößler et al. present a framework (Rößler et al., 2008) which allows the dynamic creation of a volume rendering graph. Specific fragment programs are derived from the graph to obtain and combine various GPU-based rendering techniques. However, these systems only focus on the shader development and do not provide the visual programming paradigm on all abstraction levels. Plate et al. introduced a framework for rendering arbitrarily intersecting volumes with the support of volume lenses (Plate et al., 2007). Each configuration is tiled into convex regions, which are rendered separately using a slicing algorithm. By using a graphical editor each region can be treated individually, and the resulting renderings are combined into the final image.

To summarize, several visual programming environments support modularized data processing, but to the best of our knowledge there is no one which provides a sufficient interweaving of GPU programming and application development, which is essential in order to generate interactive applications used for visual exploration.

3 ENABLING MULTI-LEVEL VISUAL PROGRAMMING

In this section, we describe our modularization of GPU-based raycasting (Krüger and Westermann, 2003), which allows to apply the visual programming paradigm on multiple abstraction levels in order to generate high-quality interactive visualization applications. GPU-based raycasting can be considered the state-of-the-art technique for interactive volume rendering. For each screen pixel a ray is cast from the virtual camera through the pixel into the scene, and the emission and absorption characteristics of each voxel intersecting the ray are calculated. In general, a voxel's intensity is not used directly, but as an argument of a color and transparency transfer function.

The rendering is performed on the graphics processing unit (GPU), the volume data is stored in a 3D volume texture. Since knowledge about the concepts behind GPU-based volume raycasting is essential, we briefly review the technique. A proxy geometry is used to represent the geometric shape of the data set. For each ray the intersection points with the proxy geometry, i. e., an entry point and an exit point, have to be determined. To do this, the color parameters of the vertices of the proxy geometry are initialized with the (color-coded) coordinates necessary for fetching the voxels from the 3D texture. In order to calculate the entry points the proxy geometry is transformed into the current view, rendered, and the result is stored in a 2D texture. Due to the initial color-coding of the vertices of the proxy geometry, during rendering the GPU's color interpolation unit automatically produces for each pixel's ray the color-coded position information of its entry point. The exit points are created in a second pass by rendering only the back-faces. During the subsequent raycasting performed within a fragment shader, the entry and exit points are used to calculate a ray's direction and length.

In our system, complex volume visualizations can be composed by visually combining several functional building blocks called *processors*, each performing a specific task. Data, such as images and volumes, flow between the processors, i. e., the output of one processor is transferred as input to one or more other processors through processor *ports*. *Inports* are used for input and *outports* for output. Different types of ports are defined to determine which inport/outport pairs are compatible and thus can be connected for transfer. Typical port types allow to transfer volume, image, or geometry data. So far several processors exist for processing volumes or images, similar as in the systems discussed in Section 2. However, additionally we have transferred the processor concept to the GPU level, by decomposing GPU-based raycasting into separate processors, which can be combined flexibly without. The challenge of this decomposition is to gain flexibility through abstraction by still allowing interactive frame rates, which requires to incorporate the boundary conditions of GPU programming. Furthermore, our decomposition leads almost automatically to an object-oriented design: processors are objects, they encapsulate information, and inheritance can be used to extend their functionality. However, the architecture of the underlying graphics system, OpenGL, is not object-oriented. For efficiency reasons OpenGL's state is determined by global variables, and polygonal data or textures are accessible via references from anywhere within an OpenGL program. Encapsulating such data into objects would result in a significant loss of performance. Thus, we had to carefully trade-off between achieving high graphics performance and following guidelines for pure object-oriented design.

3.1 Decomposing GPU-Based Raycasting

We have decomposed the raycasting process into three modules: *proxy geometry management* (PGM), *entry and exit point generation* (EEPG), and the actual *ray traversal* (RT). The EEPG uses the PGM to create entry and exit point textures from which the RT processor fetches the entry point and the exit point for each ray and performs the raycasting. This decomposition gives us a flexibility on the GPU level, which allows to reuse as well as adapt selected functionalities. Thus, for each of these three components different implementations can be generated which perform specific tasks. For instance, by modifying the proxy geometry, the part of the volume data to be visualized can be changed. An example is applying clipping planes to a cuboid-shaped proxy geometry. This leaves a clipped proxy geometry, and the entry and exit points are adjusted automatically because they are calculated using the color-coded positions of the changed vertices. More complex effects can be achieved by applying a proxy geometry processor which uses a more elaborate mesh representation for the proxy geometry and relaxes the relation between vertex positions and colors. Thus, keeping the colors constant and changing the vertex positions can produce a rendering of a deformed volume. Similarly the EEP generation can be modified to prepare a volume rendering for the integration of polygonal objects, e. g., glyphs. Assuming that the polygonal objects are opaque, it is sufficient to initialize the colors of the vertices with their positions (in texture coordinates—just the same as in the PGM) and render them onto the exit point image. Rays which intersect such polygonal objects will terminate at the foremost intersection points, and the resulting volume rendering can be combined later with an image of the polygonal objects.

Thus, the raycasting process is split into mainly three functional components, which have been realized as individual C++ classes. Instances of these classes form the processor network. To propagate the decomposition further towards the GPU, the processors themselves are also decomposed into combinable functional modules, which can be realized through shader code. For instance, the ray traversal processor uses a GLSL fragment shader for the actual computations. This shader code is separated into logical tasks whose replacement might be desired. Thus, we are for instance able to easily change the compositing without affecting the rendering performance. In the following subsection we describe this decomposition on a shader level.

```
1  vec4 rayTraversal(in vec3 first, in vec3 last)
2  {
3    vec4 result = vec4(0.0);
4
5    // calculate ray parameters
6    float tIncr, tEnd;
7    vec3 rayDir;
8    raySetup(first, last, rayDir, tIncr, tEnd);
9
10   float t = 0.0;
11   RC_BEGIN_LOOP {
12     vec3 samplePos = first + t*rayDir;
13     vec4 voxel = getVoxel(vol_, volParams_,
14                           samplePos);
15
16     // calculate gradients
17     voxel.xyz = RC_CALC_GRADIENTS(voxel.xyz,
18                   samplePos, vol_, volParams_,
19                   t, rayDir, entryPts_);
20
21     // apply classification
22     vec4 color = RC_APL_CLASSIFICATION(voxel);
23
24     // apply shading
25     color.rgb = RC_APL_SHADING(voxel.xyz,
26                   samplePos, volParams_,
27                   color.rgb, color.rgb,
28                   color.rgb);
29
30     // if opacity greater zero,
31     // apply compositing
32     if (color.a > 0.0)
33       result = RC_APL_COMPOSITING(result,
34                  color, samplePos, voxel.xyz,
35                  t, tDepth);
36   }
37   RC_END_LOOP(result);
38   return result;
39 }
```

Listing 1: The generic fragment program for ray traversal. The methods named `RC_*` are replaced at shader compile time with specialized methods.

3.2 Modularization of the Ray Traversal

In order to identify the necessary logical units, we have analyzed several shader implementations and identified four points in which they typically differ:

- **Gradient calculation**: gradients can be calculated with different methods or pre-calculated ones can be used; possibly a visualization method does not need any gradients.
- **Transfer function**: a transfer function can be one or multi dimensional; some visualization methods may use the intensity values directly without using a transfer function.

- **Shading**: the shading can be calculated in different ways (local, local with shadows, global); some visualizations do not need any shading.
- **Compositing**: the compositing determines how the current value will be combined with the already calculated ones, e. g., DVR differs from MIP.

By providing different alternatives for one or more of these functional blocks a lot of flexibility can be gained. An obvious solution is to implement for each alternative a separate function, which is executed at runtime. However, when introducing such a degree of abstraction, the limitations of GPUs have to be taken into account in order to achieve good performance results. For instance, a `switch-case` block (resp. an equivalent `if-else if` structure since GLSL does not support the former) in each case would be the straight-forward but unacceptable solution, since due to the branching this would be exceptionally time-consuming on GPUs. Since OpenGL shader programs are not compiled together with the host program during application development but by the graphics driver at runtime of the application, we have decided to generate the shader from arbitrary components at runtime. In contrast to using `uniforms`, this approach is especially beneficial when dealing with changes occurring at a low frequency. Listing 1 shows the fragment program skeleton we use. Method placeholders can be replaced at runtime with specific versions that begin with the prefix `RC_`. The `#define` directive of GLSL is used for defining macros for these placeholders.

This approach gives us the flexibility to replace function calls during runtime. To still achieve a comprehensive shader, which is not fraught by all defined alternatives for a function, we have extended GLSL with an `#include` directive known from the C preprocessor in order to be able to store different implementations of the methods in separate files. Thus we provide a set of shader includes, which define the functions to be used. To illustrate the reuse of the shader decomposition, the placeholder for the compositing methods (lines 33–35) is specified as an example below.

```
RC_APPLY_COMPOSITING(result, color, samplePos,
                     voxel.xyz, t, tDepth);
```

The parameters passed to the method contain the following information: `result` represents the accumulated values of the ray traversal up to now, `color` is the processed (i. e., classified and shaded) data value of the current position, `samplePos` is the current absolute position in the volume, `voxel.xyz` stores the gradient information, `t` is the current position on the ray, and `tDepth` contains the currently designated depth value for this parameter. The signatures of the implementing methods vary and depend on the internally needed variables. For DVR, MIP and isosurface raycasting, they look as follows:

```
1  hdrSrc +="#define RC_APPLY_COMPOSITING(result,
2                    color, samplePos, gradient,
3                    t, tDepth)";
4  switch (compositingMode_->get()) {
5  case 0:
6    hdrSrc += "compositeDVR(color, result, t,
7                            tDepth);\n";
8    break;
9  case 1:
10   hdrSrc += "compositeMIP(color, result, t,
11             tDepth);\n";
12   break;
13 case 2:
14   hdrSrc += "compositeISO(color, result, t,
15             tDepth, isoValue);\n";
16   break;
17 }
```

Listing 2: Placeholders such as `RC_APPLY_COMPOSITING` are replaced by creating a header which substitutes them with functional methods.

```
vec4 compositeDVR(in vec4 result, in vec4 color,
                  in float t, inout float tDepth);
vec4 compositeMIP(in vec4 result, in vec4 color,
                  in float t, inout float tDepth);
vec4 compositeISO(in vec4 result, in vec4 color,
                  in float t, inout float tDepth,
                  in float isoValue);
```

All these return the composited value; changes of other variables can be returned by declaring them as `inout` as it is done for `tDepth`. To choose one of these function alternatives, we generate an appropriate shader header, which defines the placeholder `RC_APL_COMPOSITING`. This header is recreated by a C++ function each time one of the replaceable functions should be exchanged (see Listing 2).

The ray initialization (`raySetup()`) as well as the begin and the end of the loop are also defined separately (`RC_BEGIN_LOOP` and `RC_END_LOOP`) in order to make them reusable in other raycasters (the variable `tDepth` which is used in the compositing header is also defined there).

4 VISUAL DEBUGGING

Debugging shader programs is complex, since besides the general problem of debugging parallel programs and the lack of debugging features such as

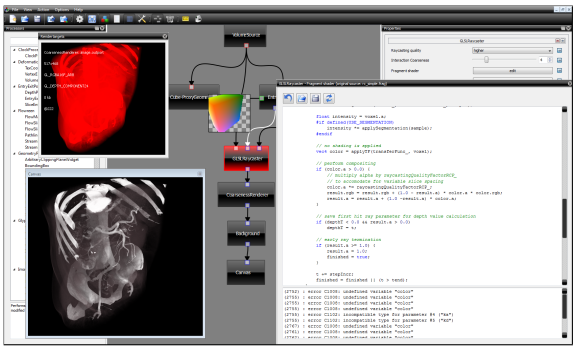


Figure 2: Shader programs can be edited in the development mode, while shader errors can be accessed (bottom right). Furthermore, intermediate output images can be inspected through tooltip windows by hovering with the mouse cursor over an arbitrary connection (middle) and the content of selected rendering targets can be inspected (top left).

breakpoints, often the interplay between different processors does not work as expected. To help software engineers to debug GLSL code, several GPU-oriented debuggers such as gDEBugger (Graphic Remedy,), glslDevil (Strengert et al., 2007), or Total Recall (Sharif and Lee, 2008) are available, which allow to inspect variables, to set breakpoints and so on. Our visual debugging features are not intended to replace such tools but rather to rapidly localize possible bugs on a higher level by inspecting intermediate results which are created as outputs of the processors. In a second step the conspicuous processors can then

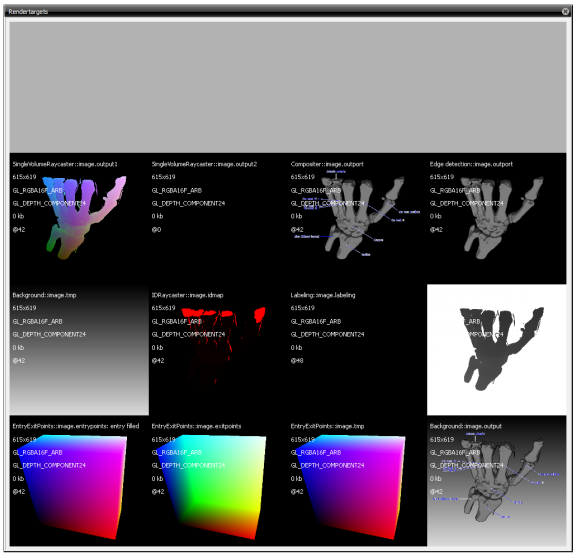


Figure 3: All produced images can be inspected using the *texture container* window. Besides the color channels also the alpha channel and the depth buffer can be visualized using pseudo-colors.

be analyzed using one of the before mentioned programs.

We support the diagnosis of this kind of errors by giving the user visual access to the output images of all processors. This can be done in different ways, either by hovering the mouse cursor over a connection between processors in the network editor where a tooltip window then shows the image which is currently transferred through this connection (see Figure 2), or by inspecting the *texture container* window (see Figure 3). This window shows the content of all images stored in the texture container. Each processor can label its output images and therefore makes it possible to relate each image to the processor by which it was generated. Furthermore, also the alpha channel and the depth buffer can be visualized using pseudo-colors.

Once an error is recognized it needs to be resolved. Since shader programs are generally compiled at runtime, a user can just reload the shader program without having to restart the application. Therefore, we have decided to integrate the used shaders as properties of the according processors. Thus, it becomes possible to simply edit a shader within our environment (see Figure 2) and serialize the changes together with the network. Thus it becomes easily possible to have different versions of the same shader, which have been adapted to the needs of a specific application case. Together with the visual debugging feature, this allows development on a GPU level directly within our visual programming environment.

5 CONCLUSIONS

In this paper we have presented a framework for the rapid prototyping of GPU-based volume visualizations with special focus on raycasting. By decomposing the GPU-based raycasting process into different functional components—which are realized by different processors—visual programming can be applied to easily create new visualizations. Thus, the paradigm can be used on all abstraction levels which need to be considered during application development. To our knowledge, this is the first approach, which allows rapid prototyping of interactive visualization applications, by providing a convenient and flexible abstraction layer, while still allowing high-quality volume ray-casting at interactive frame rates.

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