scenery — Flexible Virtual Reality Visualisation on the Java VM

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ABSTRACT
Life science today involves computational analysis of a large amount and variety of data, such as volumetric data acquired by state-of-the-art microscopes, or mesh data resulting from analysis of such data or simulations. Visualisation is often the first step in making sense of the data, and a crucial part of building and debugging analysis pipelines. It is therefore important that visualisations can be quickly prototyped, as well as developed or embedded into full applications. In order to better judge spatiotemporal relationships, immersive hardware, such as Virtual or Augmented Reality (VR/AR) headsets and associated controllers are becoming invaluable tools. In this work we introduce scenery, a flexible VR/AR visualisation framework for the Java VM that can handle mesh and arbitrarily large volumetric data, containing multiple views, timepoints, and color channels. scenery is free and open-source software, works on all major platforms and uses the Vulkan or OpenGL rendering APIs. We introduce scenery’s main features and detail example applications, such as its use in the biomedical image analysis software Fiji, or for visualising agent-based simulations.

Index Terms: Human-centered computing—Visualization—Visualization systems and tools Human-centered computing—Virtual reality

1 INTRODUCTION
Recent innovations in biology, like lightsheet microscopy [12], or Serial Block-Face Scanning Electron Microscopy (SSBFEM) [6] are now making large, spatiotemporally complex volumetric data available. However, the data acquired by the microscopes is only a means to an end: researchers need to extract results from it, and for that efficient tools are needed. This includes tools that not only enable the researcher to visualize their data, but to interact with it, and to enable them to use the tool in ways the original designer had not anticipated.

For this purpose, we introduce scenery, a flexible, open-source visualization framework for the Java Virtual Machine (JVM) that can handle mesh data (e.g. from triangulated surfaces), and multi-channel, multi-timepoint, multi-view volumetric data of virtually unlimited size [4].

The design goals for scenery were the following:

G1 Virtual/Augmented Reality (VR/AR) support: The frameworks should make the use of VR/AR in an application possible with minimal effort. Distributed systems, such as CAVEs or Powerwalls, should also be supported.

G2 Out-of-core volume rendering: The framework should be able to handle datasets that do not fit into graphics memory and/or main memory, and contain multiple channels, views, and timepoints. It should be possible to visualise multiple such datasets in a single scene.

G3 User/Developer-friendly API: The framework should have an simple API that makes only limited use of advanced features, such as generics, so the user/developer can quickly comprehend and customize it.

G4 Cross-platform: The framework should run on the major operating systems: Windows, Linux, and macOS.

G5 JVM-native and embeddable: The framework should run natively on the Java VM, and be embeddable, such that it can be used in popular biomedical image analysis tools like Fiji [27,28], Icy [4], and KNIME [1].

2 RELATED WORK
A particularly popular framework in scientific visualisation is VTK [9]: VTK offers rendering of both geometric and volumetric data, using an OpenGL 2.1 renderer. However, VTK’s complexity has also grown over the years and its API is becoming more complex, making it difficult to change internals without breaking existing applications (G5). A more recent development is VTK.js [8], which brings VTK to web browsers. ClearVolume [26] is a visualisation toolkit tailored to high-speed, volumetric microscopy and supports multi-channel/multi-timepoint data, but focuses solely on volumetric data and does not support VR/AR. Another special-purpose framework is MegaMol [8], which focuses on efficient rendering of a

1Out-of-core data is stored in tiles, with 64 bit tile indices, and each tile comprising up to 231 voxels. Therefore the limit for a single volume is 294 voxels, roughly corresponding to a cube with 231 voxels edge length.
large number of discrete particles, and provides a thin abstraction layer over the used graphics API for the developer. 3D Viewer [29] does general-purpose image visualisation tasks, and supports multi-timepoint data, but no out-of-core volume rendering, or VR/AR.

In out-of-core rendering (OOCR), the rendering of volumetric data that does not fit into main or graphics memory, existing software packages include Vaa3D/Terafly [5], which is written with applications like neuron tracing in mind, and BigDataViewer [23], which performs by-slice rendering of arbitrarily large datasets, powered by the ImgLib2 library [22]. Another application supporting OOCR is the VR neuron tracing tool [30], which lacks support for multiple timepoints and is not customizable. Invivo [12] supports OOCR and interactive development, but does not support the overlay of multiple volumetric datasets in a single view.

In the field of biomedical image analysis, various commercial packages exist: Arivis, Amira, and Imaris [21] support out-of-core rendering, and are scriptable by the user. Arivis, Amira, and also syGlass offer rendering to VR headsets, and Amira can run on CAVEm systems. Imaris provides limited Fiji and Matlab integration. Due to being closed-source, the flexibility of these software packages is ultimately limited (e.g., changing rendering methods, or adding new input devices).

3 SCENERY

With scenery, we provide a flexible framework for developing visualization prototypes and applications, on systems ranging from desktop screens over VR/AR headsets to distributed setups. The framework supports arbitrarily large volumetric datasets, which can contain multiple color channels, multiple views, and multiple timepoints. Via OpenVR/SteamVR, it supports rendering to VR headsets like the Oculus Rift or HTC Vive. scenery is written in Kotlin, a language for the JVM that makes general-purpose image visualisation tasks, while maintaining 100% compatibility with existing Java code.

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scenery is designed around two concepts: A scene graph for the scene organisation into nodes, and a hub that organises all of scenery’s subsystems — e.g. rendering, input, statistics — and enables communication between them. scenery’s application architecture is depicted in Fig. 1: scenery’s subsystems are only loosely coupled, meaning they can work fully independently of each other. The loose coupling enables isolated testing of the subsystems, and thereby we can reach 65% code coverage at the moment (the remaining 35% is mostly code that requires additional hardware and is therefore harder to test in an automated manner).

4 HIGHLIGHTED FEATURES

4.1 Realtime rendering on the JVM — G5

Historically, the JVM has not been the go-to target for realtime rendering: For a long time, the JVM had the reputation of being slow and memory-hungry. However, since the HotSpot VM has been introduced in Java 6, this is less true, and state-of-the-art just-in-time compilers like the ones used in Java 12 have become very good at generating automatically vectorized code[4]. The JVM is widely used, provides excellent dependency management via the Maven or Gradle build tools, and efficient, easy-to-use abstractions for, e.g., multithreading or UIs on different operating systems. Additionally, with the move to low-overhead APIs like Vulkan, pure-CPU performance is becoming less important. In the near future, Project Panama[6] will introduce JVM-native vectorization primitives to support CPU-heavy workloads. These primitives will work in a way similar to those provided by .NET.

Another convenience provided by the JVM is scripting: Via the JVM’s scripting extensions, scenery can be scripted using its REPL with third-party languages like Python, Ruby, and Clojure. In the future, GraalVM[5] will enable polyglot code on the JVM, e.g. by ingesting LLVM bytecode directly [2]. scenery has already been tested with preview builds of both GraalVM and Project Panama.

4.2 Out-of-core volume rendering — G2

scenery supports volume rendering of multiple, potentially overlapping volumes that are placed into the scene via arbitrary affine transforms. For out-of-core direct volume rendering of large volumes (G2) we develop and integrate the BigVolumeViewer library, which builds on the pyramidal image data structures and in-memory caching of large image data from BigDataViewer [23]. We augment this by a GPU cache for volume blocks, implemented using a single large 3D texture. This cache texture is organized into small (e.g., 323) uniformly sized blocks. Each texture block stores a particular block of the volume at a particular level in the resolution pyramid, padded by one voxel on each side to avoid bleeding from neighboring blocks during trilinear interpolation. The mapping between texture and volume blocks is maintained on the CPU.

To render a particular view of a volume, we determine a base resolution level such that screen resolution is matched for the nearest visible voxel. Then, we prepare a 3D lookup texture in which each voxel corresponds to a volume block.

1See the corresponding websites at arivis.com/en/imaging-science/imaging-science

2See https://fei.com/software/amira/

3The Vulkan renderer uses the LWJGL Vulkan bindings (see lwjgl.org), while the OpenGL renderer uses JOGL (see jogamp.org).

4For this project, we have measured the timings of performance-critical parts of code, such as 4x4 matrix multiplication. Compared to hand-tuned, vectorized AVX512 code, the native code generated by the JVM’s JIT compiler is about a factor of 3-4 slower. With the introduction of a new vectorisation API in Project Panama, this gap will close further.

5See openjdk.java.net/projects/panama

6See graalvm.org
at base resolution. Each voxel in this lookup texture stores
the coordinates of a block in the cache texture, as well as its
resolution level relative to base, encoded as a RGBA tuple.
For each (visible) volume block, we determine the optimal
resolution by its distance to the viewer. If the desired block is
present in the cache texture, we encode its coordinates in the
corresponding lookup texture voxel. Otherwise, we enqueue
the missing cache block for asynchronous loading through the
CPU cache layer of BigDataViewer. Newly loaded blocks
are inserted into the cache texture, where the cache blocks
to replace are determined by a least-recently-used strategy
that is also maintained on the CPU. For rendering, currently
missing blocks are substituted by lower-resolution data if it is
available from the cache.

Once the lookup texture is prepared, volume rendering pro-
cesses by raycasting and sampling volume values with varying
step size along the ray, adapted to the distance to the viewer.
To obtain each volume sample, we first downscale its coor-
dinate to fall within the correct voxel in the lookup texture.
A nearest-neighbor sample from the lookup texture yields a
block offset and scale in the cache texture. The final value
is then sampled from the cache texture with the accordingly
translated and scaled coordinate. With this approach, it is
straightforward to raycast through multiple volumes simulta-
neously, simply by using multiple lookup textures. It is also
easy to mix in smaller volumes which are simply stored as 3D
textures and do not require indirection via lookup textures.
To adapt to varying number and type of visible volumes, we
generate shader sources dynamically at runtime. Blending of
volume and mesh data is achieved by reading scene depth
from the depth buffer for early ray termination, thereby hiding
volume values that are behind rendered geometry.

4.3 Code-shader communication and reflection — G3
In traditional OpenGL (before version 4.1), parameter data
like vectors, matrices, etc. are communicated to shaders via
uniforms, which are set one-by-one. In scenery, instead of sin-
gle uniforms, Uniform Buffer Objects (UBOs) are used. UBOs
lead to a lower API overhead and enable variable update rates.
Custom properties defined for a certain node class that need
to be communicated to the shader are annotated in the class
definition with the @ShaderProperty annotation, scenery picks
up annotated properties automatically, and serializes them.
See Listing 1 for an example of how properties can be com-
municated to the shader, and Listing 2 for the corresponding
GLSL code for UBO definition in the shader. For procedurally-
generated shaders, a hash map storing these properties can
be used alternatively.

For all values stored in shader properties a hash is calcu-
lated, and they are only communicated to the GPU when the
values change. At the time of writing, all elementary types
(ints, floats, etc.) are supported.

Determination of the correct memory layout required by the
shader is done by our Java wrapper for the shader reflection
library SPIRV-cross and the GLSL reference compiler glslang.
This provides a user- and developer-friendly API (G3).

Furthermore, scenery supports shader factories — classes
that dynamically produce shader code to be consumed by the
GPU — and use them, e.g., when multiple volumetric
datasets with arbitrary alignment need to be rendered in the
same view.

4.4 Custom rendering pipelines — G3
In scenery, the user can use custom-written shaders and as-
sign them on a per-node basis in the scene graph. In addition,
scenery allows for the definition of fully customizable ren-
dering pipelines. The rendering pipelines are defined in a
declarative manner in a YAML file, describing render targets,
render passes, and their contents. Render passes can have
properties that are adjustable during runtime, e.g., for ad-
justing the exposure of a HDR rendering pass. Rendering
pipelines can be exchanged at runtime, and do not require a
full reload of the renderer — e.g., already loaded textures do
not need to be reloaded.

The custom rendering pipelines enable the user to quickly
switch between different pipelines, thereby enabling rapid prototyping of new rendering pipelines. We hope
that this flexibility stimulates the creation of custom pipelines,
e.g., for non-photorealistic rendering, or novel applications,
such as Neural Scene (De)Rendering [19, 31].

4.5 VR and preliminary AR support — G1
scenery supports rendering to VR headsets via the Open-
VR/SteamVR library and rendering on distributed setups,
such as CAVES or Powerwalls — addressing G1. The modules
supporting different VR devices can be exchanged quickly
and at runtime, as all of these implement a common interface.
In the case of distributed rendering, one machine is desig-
nated as master, to which multiple clients can connect. We use
the same hashing mechanism as described in Section 4.3 to
determine which node changes need to be communicated over
the network, use Kryo for fast serialization of the changes,
and finally ZeroMQ for low-latency and resilient network
communication. A CAVE usage example is shown in Fig. 2.

We have also developed an experimental compositor that
enables scenery to render to the Microsoft Hololens.

4.6 Remote rendering and headless rendering
To support downstream image analysis and usage settings
where rendering happens on a powerful, but non-local com-
puter, scenery can stream rendered images out, either as raw
data or as H264 stream. The H264 stream can either be saved
to disk or streamed over the network via RTP. In the streaming
video case, all produced frames are buffered and processed in
a separate coroutine, such that the rendering performance is
not impacted.

Listing 1: Shader property example

```java
// Define a matrix and an integer property
@ShaderProperty var myMatrix: GLMatrix
@ShaderProperty var myIntProperty: Int
// For a dynamically generated shader: Store <-
// properties as hash map
@ShaderProperty val shaderProperties = HashMap<String, Any>()
```

Listing 2: GLSL code example for shader properties

```glsl
layout(set = 5, binding = 0)
uniform ShaderProperties {
    int myIntProperty;
    mat4 myMatrix;
};
```

7See github.com/KhronosGroup/SPIRV-cross for SPIRV-cross and
github.com/scenerygraphics/spirv-cross for our wrapper library,
spirvcross.

8See github.com/EsotericSoftware/Kryo for Kryo.
scenery can run in headless mode, creating no windows, enabling both remote rendering on machines that do not have a screen, e.g., in a cluster setup, or easier integration testing. Most examples provided with scenery can be run automatically (see the ExampleRunner test) and store screenshots for comparison. In the future, broken builds will be automatically identified by comparisons against known good images.

5 Example Applications

5.1 sciview

On top of scenery, we have developed a plugin for embedding in Fiji/ImageJ2 — sciview, fulfilling G5. We hope it will boost the use of VR technology in the life sciences, by enabling the user to quickly prototype visualisations and add new functionality. In sciview, many aspects of the UI are automatically generated, including the node property inspector and the list of Fiji plugins and commands applicable to the currently active dataset. sciview has been used in a recent SPIM pipeline. In Supplementary Video 2, we show sciview rendering three overlaid volumes from a fruit fly embryo, a still frame of that is shown in Figure 3.

5.2 Agent-based simulations

We have utilized scenery to visualize agent-based simulations with large numbers of agents. By adapting an existing agent- and physics-based simulation toolkit, we have increased the number of agents that can be efficiently visualized by a factor of 10. This performance improvement enables previous studies of swarms with evolving behaviors to be revisited under conditions that may enable new levels of emergent behavior. In Figure 4, we show 10,000 agents using flocking rules inspired by to collectively form a sphere.

5.3 Evaluating simulator sickness for VR control of microscopes

We have used scenery in a preliminary study of VR control for state-of-the-art volumetric microscopes. In this study with 8 microscopy experts, we investigated whether users tend to suffer from motion sickness while using our interfaces. We found an average SSQ score of 6.2 ± 6.7, which is very low, indicating that users very well tolerated our VR rendering of live microscopy data and interacting with it. A demo of such an interface is shown in Supplementary Video 1.

6 Conclusions and Future Work

We have introduced scenery, an extensible, user/developer-friendly rendering framework for geometric and arbitrarily large volumetric data and demonstrated its wide applicability in a few use cases. In the future, we will introduce better volume rendering algorithms (e.g. [13, 16]) and investigate their applicability to VR settings. Furthermore, we are looking into providing support for out-of-core mesh data, e.g. using sparse voxel octrees [17, 18]. On the application side, we are driving forward projects in microscope control (see Section 5.3) and VR/AR augmentation of lab experiments.

7 Software and Code Availability

scenery, its source code, and a variety of examples are available at github.com/scenerygraphics/scenery and are licensed under the LGPL 3.0 license. A preview of the Fiji plugin sciview is available at github.com/scenerygraphics/sciview.

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