



Optimizing workflow for virtual environments using Vulkan Model Viewer and Exporter

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*I would like to dedicate this report to my family, friends and lecturers who
have supported me throughout my degree*

Abstract

Computer graphics is a rapidly growing field that is vital in many industries that rely on digital graphics including scientific research, simulations, education and training, entertainment and more. The flexibility of this field and the increase in computing resources is what makes it so powerful and provides real-world benefits in ways not previously observed before the use of graphics software.

This report presents my final year project an application built from the ground up using the latest technologies for 3D graphics rendering. Its goal is to be easy to use, and performant and include a collection of tools for graphics manipulation that users can take advantage of when designing and building virtual environments.

Declaration

I hereby certify that this report constitutes my work, that where the language of others is used, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas, expressions, or writings of others. I declare that this report describes the original work that has not been previously presented for the award of any other degree or institution.

April 11, 2023

Date

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Signature

Contents

	Page
1 Introduction	1
1.1 Overview	1
1.2 Aims and Objectives	1
1.2.1 Easy-to-use	2
1.2.2 Efficient	2
1.2.3 Encryption and model format	2
1.3 Stakeholders	3
1.4 Legal	3
1.4.1 License	3
1.4.2 Security	3
1.4.3 Intellectual property	3
1.5 Social	4
1.5.1 Accessibility	4
1.6 Ethical	4
1.6.1 Software	4
1.6.2 Deceptive design	4
2 Technology Review	5
2.1 Tools	5
2.1.1 Project Management	5
2.1.2 Microsoft Visual Studio 2022	6
2.1.3 RenderDoc	7
2.1.4 AMD Radeon GPU Profiler	8
2.2 Programming Language	9
2.3 Rendering API	10
2.4 Libraries	11
2.4.1 User Interface	11
2.4.2 Encryption	11
2.4.3 Serialisation	11
2.4.4 Additional libraries	12
3 Design	12
3.1 Branding	12
3.1.1 Project Name	12
3.1.2 Logo	12
3.2 VCS Architecture	13

3.3	Programming Conventions	13
3.4	Project Architecture	15
3.5	Renderer Architecture	16
3.6	User Interface	17
3.6.1	Main Viewport	18
3.6.2	Global Controls	18
3.6.3	Model Controls	18
3.6.4	Logs	18
3.7	Custom file format and encryption	19
3.7.1	File format	19
3.7.2	Encryption and Decryption	19
4	Implementation	19
4.1	Overview	20
4.2	Window System	20
4.3	Rendering System	21
4.3.1	Renderer Context	22
4.3.2	Swapchain	22
4.3.3	Frame synchronization	22
4.3.4	Framebuffers	24
4.3.5	Texture sampling	24
4.3.6	Deferred Rendering Pipeline	24
4.3.7	Dynamic Uniform Buffers	24
4.3.8	Models	25
4.3.9	Entities	26
4.3.10	Camera	26
4.3.11	Lighting	28
4.4	User Interface	31
4.4.1	Controls	31
4.4.2	Fonts and Icons	32
4.4.3	Menu Bar	32
4.4.4	Load Model Window	32
4.4.5	Export Model Window	33
4.4.6	Settings Window	34
4.4.7	Object gizmo	34
4.5	Logging system	35
4.6	Encryption and custom System	36
4.7	Custom File Format	36
4.8	Distribution	36
4.8.1	Versions	36

4.8.2	Website	37
4.8.3	Example models	37
4.8.4	Documentation	38
5	Evaluation	38
5.1	Distribution	38
5.2	Programming language	39
5.3	Time Management	40
5.4	Performance	40
5.4.1	Compilation Performance	41
5.4.2	Runtime Performance	41
5.4.3	Hardware	42
5.5	User Feedback	42
6	Related Work	43
7	Reflection	43
7.1	Choice of rendering API	43
7.2	Development logs	43
8	Future Work	44
8.1	Rendering	44
8.1.1	Multiple rendering APIs	44
8.1.2	Frustum Culling	44
8.1.3	Spatial Acceleration Structures	45
8.1.4	glTF Support	47
8.2	Cross Platform	48
8.3	Networking Support	48
8.4	Encryption	48
8.5	Version Control	48
8.6	Reduce library dependencies	49
8.7	Accessibility	49
9	Conclusion	50
10	References	53
11	Appendices	54
11.1	Rendering API history	54
11.2	Camera transformation code	55

1 Introduction

Computer graphics is a vast area within the field of Computer Science. Since its conception in the early 1960s, it has been used for different purposes including gaming, film, scientific research, education, architecture, engineering, medicine and more recently within vehicles. This is a testament to how versatile this field has become.

Many different rendering applications already exist including Unreal Engine [1], Unity [2] and RenderMan [3] just to name a few. These applications are known as “3D creation tools” that provide a plethora of features and functionality giving the users the freedom to create anything they need.

A common theme that can be observed with these engines is that they have a lot of different tools and features as a result of decades of work. This inadvertently introduces several issues such as increased complexity, a steep learning curve as well as high-end hardware requirements.

To address these issues, I introduce my final year project, Vulkan Model Viewer and Exporter (VMVE). An application developed in the domain of Computer Graphics to provide an easy-to-use and efficient platform for 3D graphics rendering. The project does not aim to replicate the functionality of existing rendering engines but instead to purposely implement a small but specific subset of features that are used for common graphics-related tasks. These include constructing virtual environments, simulating the effect of light on 3D geometry and securing digital assets through the use of encryption.

1.1 Overview

This report presents the development of the project from start to finish and is structured such that it outlines each aspect of the project’s development in chronological order. There are a total of five key sections in this report. The introduction, design, implementation, evaluation and finally, future work.

1.2 Aims and Objectives

Successfully designing, implementing and evaluating a project relies on a set of aims and objectives to be fully defined. VMVE has three main aims and consists of several objectives that outline the concrete steps required to achieve those aforementioned aims.

1.2.1 Easy-to-use

The first goal of VMVE is to be “easy-to-use”. This means that the application should not have a steep learning curve and users with little to no prior experience with 3D rendering software and the underlying technology can use the application to achieve their intended goals.

Ensuring that this aim can be achieved comes down to various design decisions related to the user interface, the language used and documentation. In regards to the application user interface, it must be designed intuitively and reduce the amount of friction between the user and their end goal.

Furthermore, the language used throughout the user interface must reduce if not eliminate jargon. A simple example could be to use the word “Move” instead of “Translate” when referring to objects in the virtual environment and as such, would make the application more accessible.

1.2.2 Efficient

The second aim of the application is to be as efficient as possible and subsequently lower the hardware requirements. The application’s efficiency and aims vary based on the component in question.

– CPU – GPU – Memory – Storage

1.2.3 Encryption and model format

The last of the three main goals is for the application to include its own model format that makes use of encryption to safely secure a user’s digital assets as previously mentioned. The motivation for this functionality formed as a result of the increase in theft regarding digital assets. A prime example of this was the recent data leak that affected Rockstar Studios and their upcoming game (Grand Theft Auto 6) [4].

VMVE would be able to provide a platform to encrypt these assets and only unlock them using a special key that only the user will know. This ensures that in the event of digital assets begin obtained by third parties, they cannot be used. This requires several key elements to work together to achieve this aim.

The raw model must be able to be encrypted using different types of encryption algorithms. In addition to this, VMVE must include a parser that

can read the internal structure of the encrypted file format and successfully load the model.

1.3 Stakeholders

- TODO: Users

1.4 Legal

Legal considerations are important when distributing an application intended to be used in production. The project and subsequently the application must abide by local laws and regulations.

1.4.1 License

VMVE is to be licensed under the MIT license [5]. This ensures the application can be used without restriction allowing for it to be copied, modified as well as distributed.

1.4.2 Security

Additionally, security must be taken into account when developing the application. As mentioned earlier, VMVE will include the ability to secure critical assets including 3D models. This will be achieved using encryption by making use of a secret key and initialization vector.

When developing the system, it is, therefore, important to ask questions such as “How will this data be kept secure?” and “Does the application store or send any private data?”.

Throughout the development of this project, the application will not contain any networking functionality. This ensures that all data remains local to the application and the user’s device.

1.4.3 Intellectual property

Given the domain in which the application is intended to be used, such as handling third-party 3D assets by importing and exporting geometry data. VMVE mustn’t infringe upon the copyright of those who own the models. One such example includes not modifying the geometry data unless specified by the user. Since this will be a new application, a lot of the intricacies behind Intellectual Property (IP) need to be further defined and

taken into account based on user feedback. VMVE will not modify any of the data being imported and only change the visual appearance based on several factors including rendering settings, lighting, translation, rotation and scaling.

1.5 Social

VMVE must also take into account social considerations for those using the application to provide a consistent user experience.

1.5.1 Accessibility

Accessibility is a vital aspect that needs to be addressed throughout the development to ensure the application is useable for those with disabilities.

1.6 Ethical

1.6.1 Software

One of the main ethical considerations that must be taken into account is the computation that the application will perform internally. The technical implementation details are not accessible to users as the source code is not open source. Therefore, individuals do not know exactly what the software is doing during runtime.

To ensure that VMVE remains ethical, the application will not perform any additional computations that are not strictly required for 3D rendering. Furthermore, the application will not store or send any data as this is not required.

1.6.2 Deceptive design

Deceptive design also known as “Dark patterns” refers to designs/tricks that manipulate users into performing certain actions without their informed consent. VMVE will make use of a user interface, however, during the design and implementation stages extra effort will be spent on ensuring that no such design pattern is introduced. This will greatly benefit users and thus, increase the overall user experience.

2 Technology Review

This project made use of various technologies at different stages throughout the development process and was a key aspect in helping achieve the final goal of developing a 3D model viewer and exporter.

Technologies are categorized into two areas based on the impact they have on the project such as direct and indirect influence. A technology that has a direct impact means that it assisted in some way in the implementation of the project. Whereas, indirect impacts are technologies that are used in some areas not directly responsible for the outcome of the project such as project management.

2.1 Tools

- TODO: Explain the types of tools used and their significance.

2.1.1 Project Management

A Version Control System (VCS) is a tool used for backing up and/or collaborating with developers on a project. The use of a VCS was an obvious choice as this would provide a platform on which the project source code could be hosted. This gives me the peace of mind of knowing that if for some reason a local copy of the project is lost or corrupted then another copy is safely hosted on the servers managed by the VCS.

Another key feature of a VCS is project management. These types of systems provide various tools that greatly benefit developers. One such feature is known as a “commit” which records any changes made to a particular repository at that moment in time. Developers use commits to view changes that occur at each stage but also, provide means of reverting to previous versions of particular sections, files or even an entire repository. Due to the length and complexity of this project, tools such as this provided by a VCS are invaluable throughout the development process.

The version control system that was chosen was Git [6]. This is the most widely-used, free and open-source VCS. Git can be used in several ways such as by installing Git onto a server manually or by using existing platforms that are built on top of Git. A few examples include GitHub, GitLab and Bitbucket. By far the most popular option is GitHub which is the platform that I am most familiar with and therefore, GitHub will be the platform of choice for this project.

The VMVE project is hosted on GitHub as a private repository <https://github.com/ZOulhadj/vmve/>

GitHub as well as providing hosting for the repository also provides different features related to task management. One such feature is known as GitHub issues. This will be used as the task tracker in which “posts” are created that would track outstanding tasks including the priority, current progress and the expected deadline. Figure 1 shows a preview of the Kanban board. It consists of three main columns used to categorize an issue including backlog, in progress and done.

When an idea for a new feature is thought of or a bug within the application is discovered a GitHub issue is created and moved to the “Backlog”. This is used to document a particular task that needs to be worked on in the near future.

Then once a specific issue is ready to be worked on/resolved, it’s moved to the “In Progress” column. As the issue is being addressed, key points of discussion are added as comments to the issue for documentation purposes.

Lastly, once the task has been completed, the GitHub commit that includes the fix is referenced in the issue and is then finally marked as complete by being moved to the “Done” column.

2.1.2 Microsoft Visual Studio 2022

Developing a program that runs directly on the underlying operating system requires a compiler. This is a program that parses source code and generates assembly instructions that the Central Processing Unit (CPU) will be able to understand and therefore, execute. Microsoft Visual Compiler (MSVC) also known as CL will be the compiler of choice. This is a compiler that comes bundled with the Microsoft Visual Studio Integrated Development Environment (IDE).

The IDE also provides debugging functionality that will be used extensively to fix crashes, bugs and generally ensuring that the application runs as expected [7].

Some additional tools will be used that will further improve the ease of development. Visual Studio Assist X [8] is one such tool. This is a Visual Studio extension that provides many useful features that the base IDE does

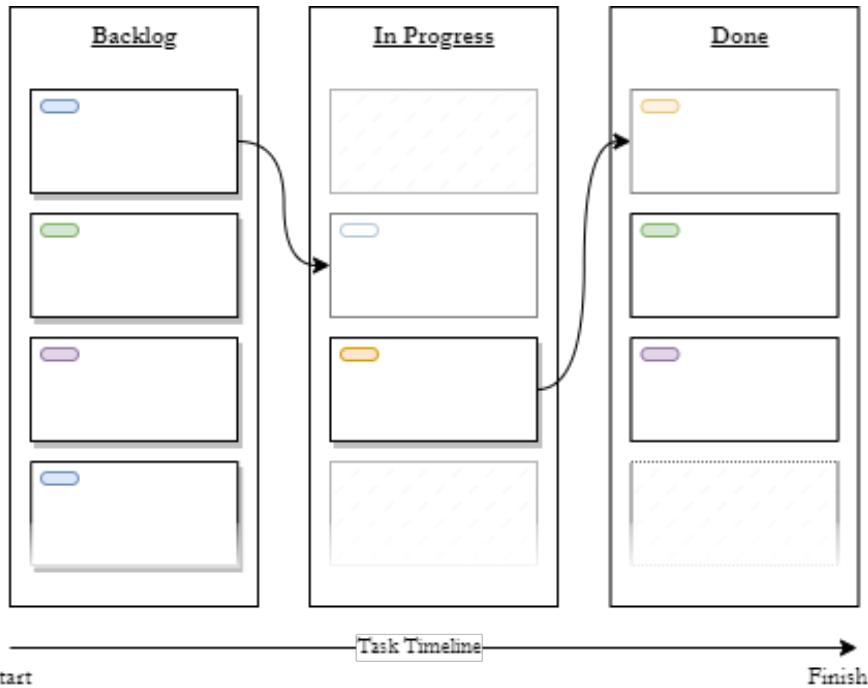


Figure 1: Kanban design

not provide such as reliable symbol renaming, file symbol outlining, quick file searching and much more.

2.1.3 RenderDoc

As well as using software for debugging on the CPU, there also exists software that allows for debugging the Graphics Processing Unit (GPU). More specifically, these tools allow for analyzing per-frame data as well as detailed frame synchronization metrics.

RenderDoc developed by Baldur Karlsson can be used to inspect different rendering Application Programmable Interfaces (APIs) including individual frames and the entire state [9]. This ensures that you can debug specific GPU related bugs such as model data, textures, rendering commands etc. An example of this can be seen in figure 3

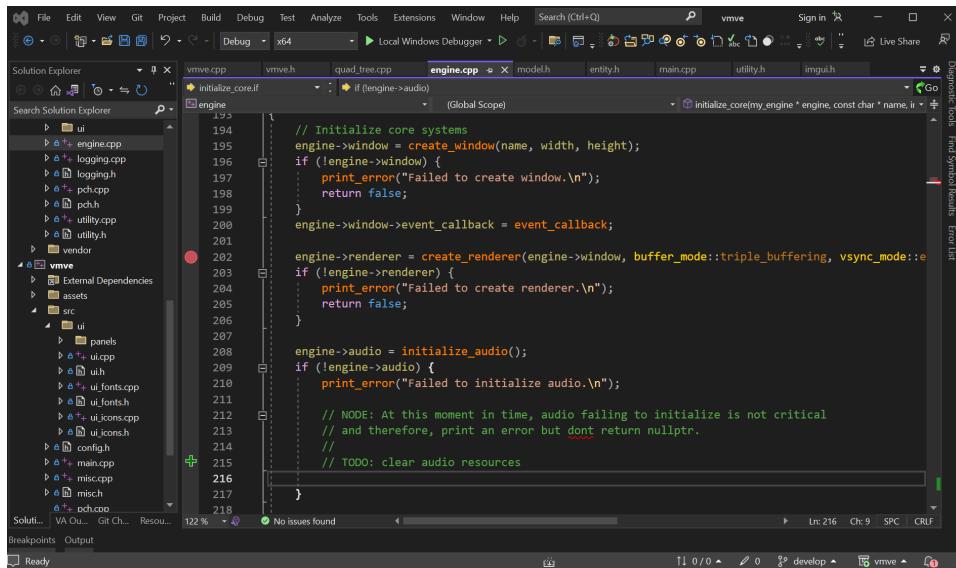


Figure 2: Microsoft Visual Studio

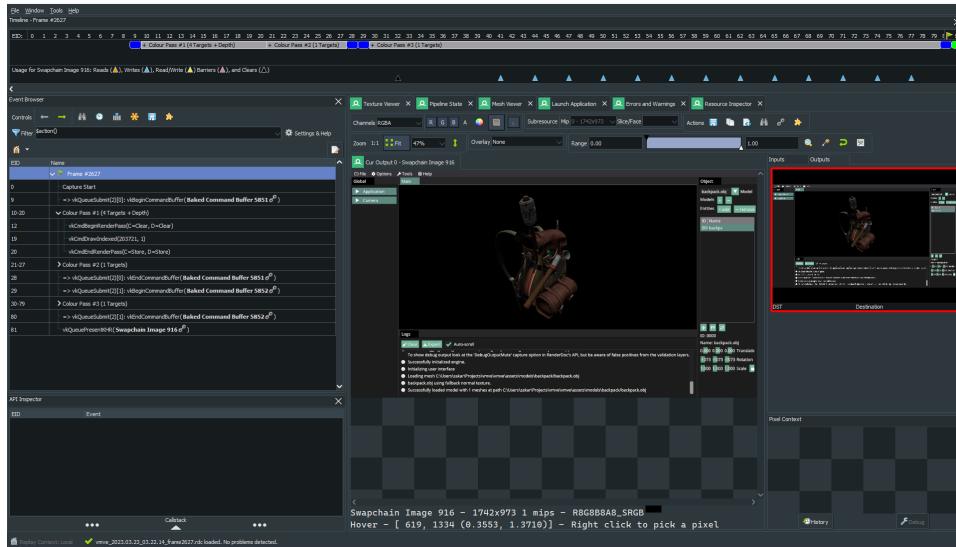


Figure 3: RenderDoc

2.1.4 AMD Radeon GPU Profiler

Similarly to RenderDoc, AMD has its own GPU profiling tool called “AMD Radeon GPU Profiler” [10]. This tool is only available for AMD-supported

GPUs which is ideal as the hardware going to be used throughout development meets this requirement. The tool analyzes per-frame data which subsequently provides insightful performance metrics and can be seen in action in figure 4.

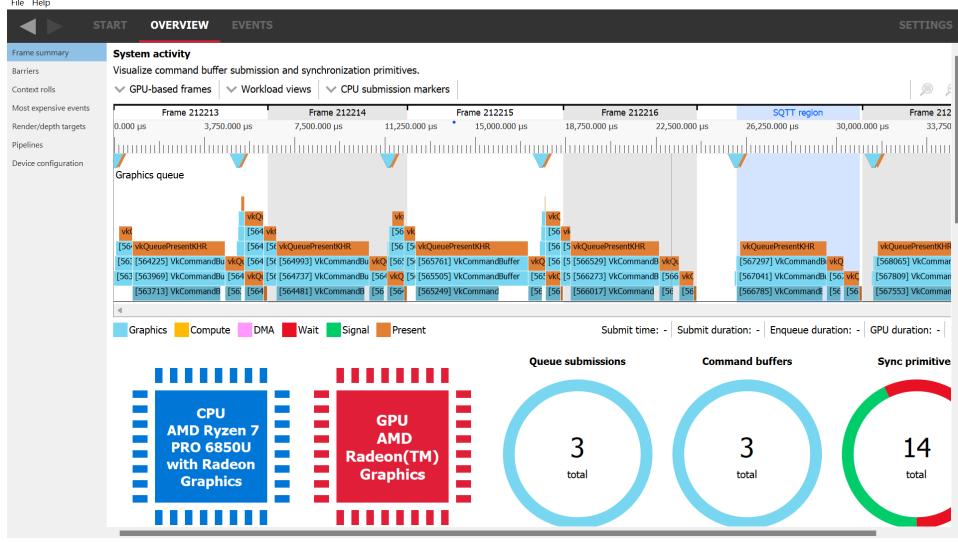


Figure 4: AMD Radeon GPU Profiler

2.2 Programming Language

The application needs certain requirements to be met regarding performance. For example, the application must use a high-performing programming language, allows for low-level memory access and can be compiled into an executable.

The language chosen for this project was C++ 23. There were two main reasons why this specific programming language was chosen. Firstly, it's the language that I have the most experience with which will significantly help during the implementation stages of the project. Secondly, the C++ Standard Template Library (STL) was one of the key reasons why C++ will be used. It provides many prebuilt data structures, containers and algorithms including “`std::vector`”, “`std::string`” and “`std::find`” to name a few. Furthermore, it saves time as I would not have to implement a custom solution in the limited time frame. Other language features that solidified by choice include, function overloading, templates, compile-time expressions,

direct memory access and generally faster performance compared to higher-level languages such as Python and Javascript.

2.3 Rendering API

A rendering API is a set of instructions that acts as an intermediary and allows for an application to make use of a systems GPU. There are several different rendering APIs that exist including OpenGL, Vulkan, Direct3D 11 and Direct3D 12. Appendix section 11.1 goes into great detail explaining the history of rendering APIs and the differences between them.

OpenGL and Direct3D 11 are previous generation APIs whereas Vulkan and Direct3D 12 are using the latest technologies. Each of these has its benefits and disadvantages. The image below shows a table that compares each of these with specific types of functionality.

	Cross Platform	Finer control	Multithreading
OpenGL	✓	✗	✗
Vulkan	✓	✓	✓
Direct3D 11	✗	✗	✗
Direct3D 12	✗	✓	✓

Figure 5: Rendering API comparison

Figure 5 shows that Vulkan has the most amount functionality including the ability to run on different operating systems, finer rendering control and support for multithreading.

In addition to Vulkan inhibiting the most functionality, there are numerous other reasons why this API is the most suitable for VMVE. Firstly, Vulkan is extremely verbose as it exposes the technicalities related to the GPU and requires the application to implement the basic functionality as opposed to the driver. This reduces the complexity of the display driver and can potentially increase performance as it no longer needs to make assumptions about the application and the commands being issued as the entire state of

the rendering pipeline is predefined. Using Vulkan also implicitly helps understand the complex inner workings of graphics development and working with the GPU.

2.4 Libraries

The application will make use of different external libraries to speed up development due to the short timeframe.

2.4.1 User Interface

Users will need a way of interacting with VMVE and the 3D environment. This will be achieved through the use of a user interface in which the user can directly manipulate the application. As mentioned earlier, VMVE is an application that uses the GPU for rendering and therefore, the UI will have to interact with the GPU. To reduce the development time of this particular aspect of the application, the decision was made to make use of a preexisting library.

The library of choice was Dear ImGui [11]. This is an immediate-mode user interface library that provides an API to render UI elements.

2.4.2 Encryption

VMVE will include its own model file format. This is a special format that will be encrypted as standard. Implementing encryption is a very complex area that can be considered an entire project on its own. Instead, the project will make use of a well-known encryption library known as Crypto++ [12]. This is a C++ library that provides various algorithms including AES, Diffie-Helm,

2.4.3 Serialisation

In addition to encrypting the model data, the custom file format will need to store additional information such as application version and encryption type. Therefore, VMVE must be able to serialize the data when saving to disk as well as deserialize when loading a “.vmve” model. To achieve this, the cereal C++ library will be used [13]. This library allows for fast and efficient data serialization into different formats such as compact binary encodings, XML or JSON.

2.4.4 Additional libraries

The other libraries used in VMVE can be seen in the list below.

assimp Model loading

glm Mathematics

stb Image loading

vma Vulkan memory allocator

volk Vulkan meta-loader

3 Design

The next stage of the project was designed and occurred between milestones two and three.

Having discussed the different technologies being used in VMVE, they must now be evaluated and incorporated into the design of VMVE and its various subsystems.

3.1 Branding

The branding i.e the look of the application was an important factor during the design as it will be presented to users and can directly influence the user experience. Furthermore, being recognizable can result in greater number of users.

3.1.1 Project Name

VMVE stands for “Vulkan Model Viewer and Exporter”. The name is split into two. The first is “Vulkan” the other is “Model Viewer and Exporter”. The rendering API used to render 3D digital assets is Vulkan and hence the first part of the name. The second part is because the application will include functionality such as importing and exporting models into a custom file format as mentioned in section 2.4.2.

3.1.2 Logo

There are two versions of the VMVE logo that was designed and intended to be used in different situations. The first is the complete logo as seen below

in figure 6 which is referred to as the “large logo”. It contains the icon and the name of the application.



Figure 6: VMVE Large Logo

The second version is designed to be minimal and therefore, only consists of the icons itself.

3.2 VCS Architecture

As the only developer for this final year project, the design and architecture will remain as simple as possible while still providing the core requirements. Figure 8 shows the proposed version control architecture and includes two branches named “main” and “develop”. Develop will be the primary branch used throughout the implementation stages.

Main will be used as a stable branch that is only updated for each official release. This would occur for each project milestone such that for “Sprint 1” a pull request will be made from develop to main and this will be tagged as v0.0.1 and likewise “Sprint 2” will be tagged as v0.0.2.

3.3 Programming Conventions

From the beginning, the projects source code and overall architecture were to adhere to the C++ Core Guidelines [14] to ensure that the project follows best practices.

A significant amount of consideration was spent planning out a suitable project-wide programming style. In regards to naming, section NL.10 of the core guidelines recommend using the snake case style as it follows the standard libraries naming convention. Since the project has no existing code



Figure 7: VMVE Small Logo

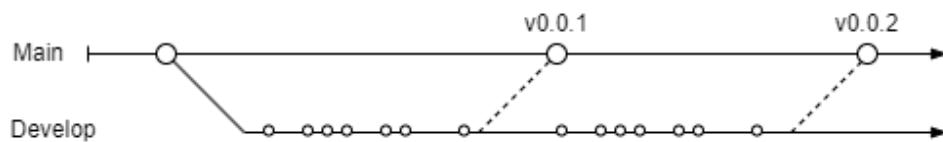


Figure 8: Git branch design

base and therefore, no existing convention to follow, the project will make use of the underscore style for types, functions and variables.

Additionally, section NL.17 states that the use of the “K&R” indentation style [15] should be used as it preserves vertical space whilst maintaining readability. In other words, reducing vertical line height for code blocks such as “if, else, while and for” allowing for more lines of code to be visible at any given point whilst allowing for a more distinct separation of structures and functions.

The combination of these two specific conventions in regards to source code style can be seen in figure 9.

```

1   struct foo
2   {
3       int a;
4   };
5
6   void bar(int a)
7   {
8       if (a) {
9           printf("This is a example.\n");
10      } else {
11          printf("This is another example.\n");
12      }
13  }
14

```

Figure 9: Source code convention

3.4 Project Architecture

VMVE will be a combination of two projects. The “Engine” project also known as the core of VMVE will contain the fundamental implementation details. This includes the window, renderer, ui and other subsystems. This project will be distributed as a library file (.lib) that other projects can import for specific use cases.

The “VMVE” project will include the “Engine” project by importing the .lib file.

A high-level overview of the project architecture can be seen in figure 10.

There is another key reason why, I will isolate the core of VMVE into its own project instead of combining it into one program. The reason being is have the core be a library that can be used in not just VMVE but also other projects in the future.

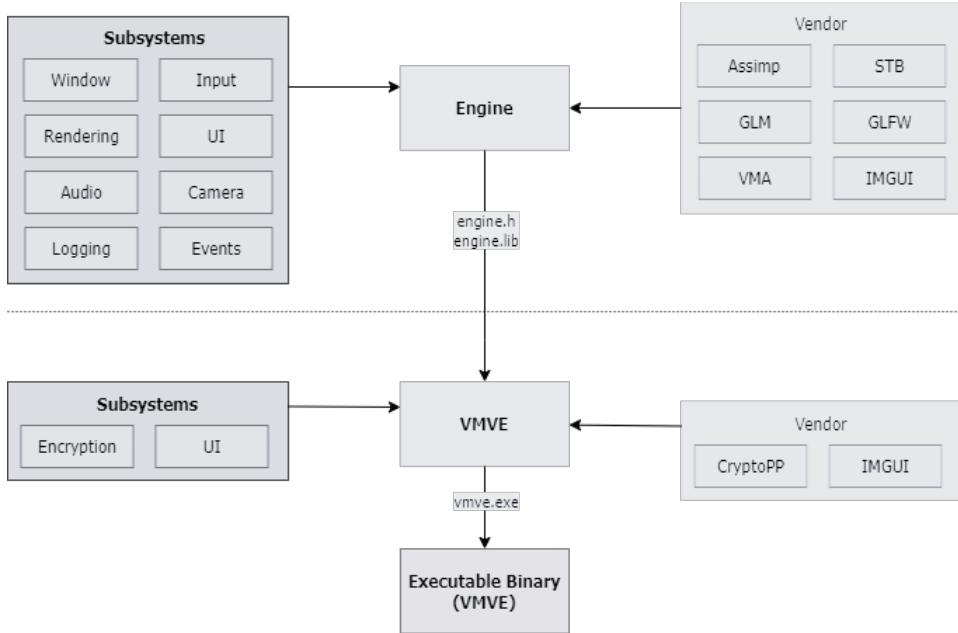


Figure 10: Project Architecture

- Reason for choosing 64bit program. goes beyond 4GB address space limit in 32bit programs. supports modern hardware
- Functional over object oriented - POD (Plain old data types) - Less boilerplate code (getters and setters) - Easier access to member variables
- Editor UI design and the reason for it for this particular application? - UI allows for interaction with underlying system during runtime. - Viewport style editor meaning that all controls can be positioned around the viewport and the main rendering occurs at the center of the screen. - VMVE file format - Header - Data - Encryption - AES (128, 256 bits for key length)

3.5 Renderer Architecture

As mentioned in section 2.3. Vulkan will be the rendering API of choice for VMVE. The API is extremely verbose giving the programmer the flexibility to control every aspect of the GPU. When interacting with Vulkan throughout the engine a certain degree of encapsulation is necessary to reduce the amount of effort required to implement functionality as a result of VMVEs verbose API.

To achieve this, the renderer must be properly designed so that flexibility is not lost whilst still simplifying the API. Figure 11 shows the proposed renderer architecture which makes distinctive boundaries and encapsulates key systems.

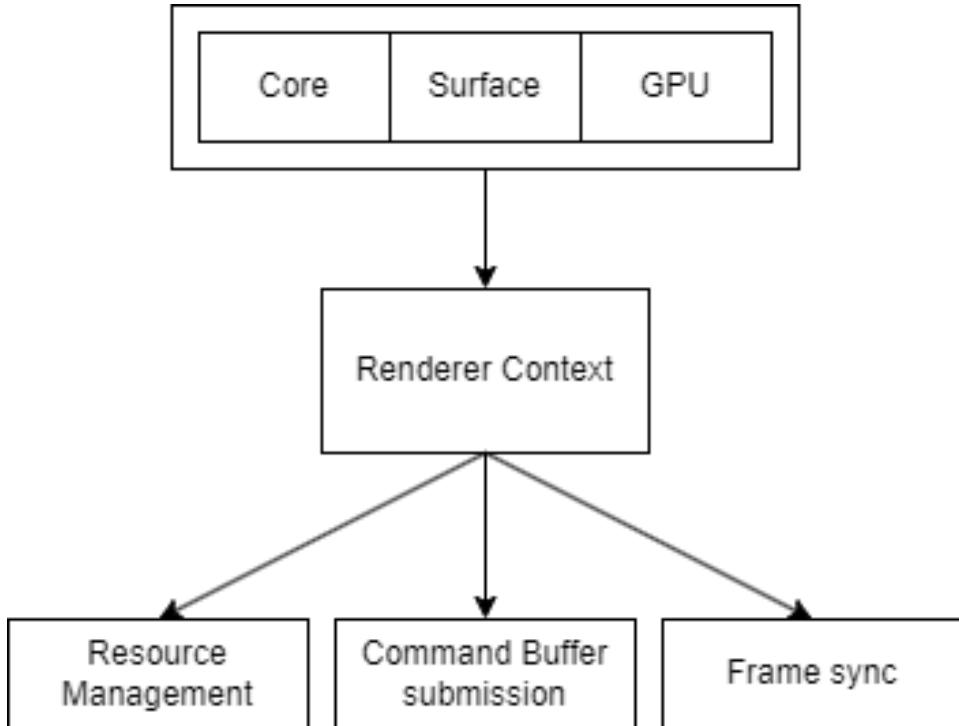


Figure 11: Renderer Architecture

3.6 User Interface

Designing the user interface was the next step as part of the design stage of the project. Figure 12 shows the initial user interface wireframe that includes four main elements titled “Global Controls”, “Logs”, “Model Controls” and “Main Viewport”. Each of these UI elements is located in their respective windows which are designed in such a way that common controls are grouped and located appropriately if not within the same panel.

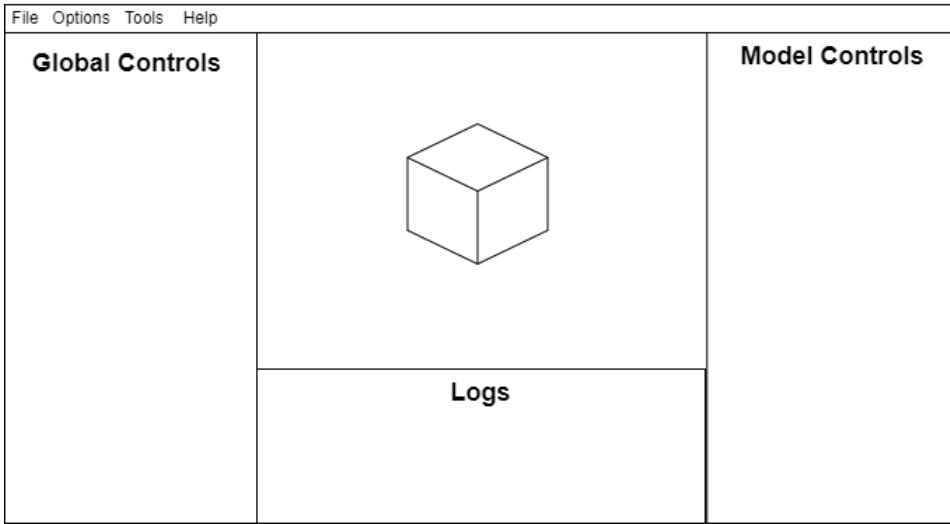


Figure 12: UI Design

3.6.1 Main Viewport

The main viewport is located in the center of the window and is the main feature of the user interface. The viewport displays the virtual environment and

3.6.2 Global Controls

3.6.3 Model Controls

Each model loaded into the application and currently highlighted is shown model-specific information within the model controls panel. This panel will include various

3.6.4 Logs

The logs panel is designed to contain all internal messages that the application prints out. These messages will then be displayed within the logs panel. Each log message will be categorized as either log, warning or error. Depending on which log type the message is, it will be shown in a different color such as white, orange or red respectively.

This is designed so that the user will have a clear understanding of the

internal state of the application.

3.7 Custom file format and encryption

3.7.1 File format

VMVE will include its own file format that allows for model data to be encrypted for security purposes. Figure 13 shows the proposed internal structure of the custom file format. It includes a 48-byte header that will consist of a version and the method used for encryption. The purpose of the version is to check for compatibility between different VMVE versions. In addition to this, this can be used to convert older versions of VMVE to newer versions.

The second item in the VMVE header is the encryption mode. This allows for the VMVE to know which algorithm must be used to decrypt the data.

- TODO: Update picture to use a smaller header size by using a packed uint32_t for the version



Figure 13: VMVE File internal structure

3.7.2 Encryption and Decryption

- encrypting – – loading model – encrypting model – export model
- decrypting – – load model – check version – check encryption mode – attempt to decrypt – load model into VMVE

4 Implementation

This section of the report presents the technical implementation details of VMVE. This section is presented in order of initialization i.e starting at the core of the application and discussing each subsequent system.

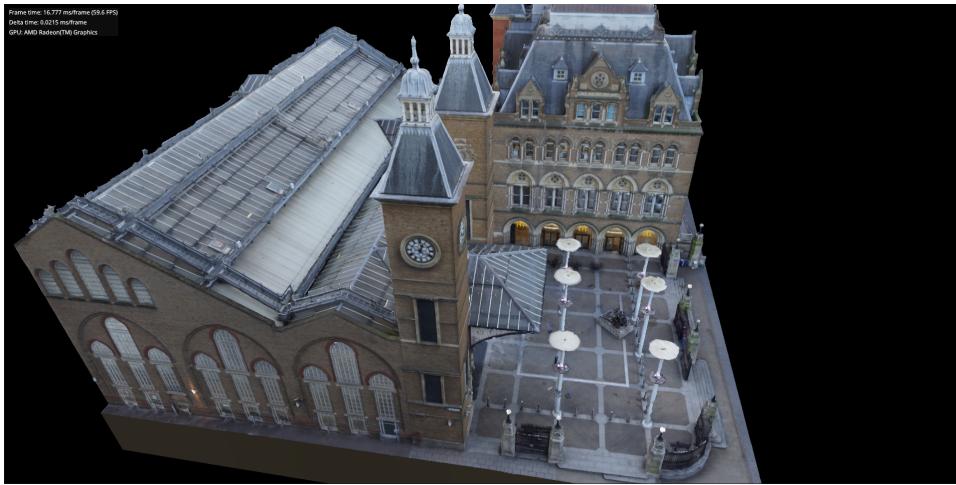


Figure 14: Liverpool Street Station renderer model

4.1 Overview

Figure 15 shows the general overview of the application and the various stages that occur during initialization, runtime and shutting down.

4.2 Window System

The first system within VMVE that gets initialized is the window. This system is responsible for creating a desktop window based on a series of configuration options specified at the start of the application. These options include the window width, height and name. Internally, VMVE uses the lightweight GLFW library to handle window creation. The purpose of this library is to provide an API which is cross-platform and allows applications to easily create windows on different operating systems.

Under the hood, on Windows, GLFW uses the Win32 API provided by Microsoft.

In addition to the window creation, various function callbacks are created which allows VMVE to handle specific events such as window resizing, input, cursor position etc.

```

1
2 int main()
3 {
4     // begin application initialization
5     create_window(width, height, name);
6     create_renderer();
7     create_audio();
8     create_ui();
9
10    // set default configuration options
11    create_camera();
12
13    // begin application rendering
14    while (running)
15    {
16        update_renderer();
17
18        render_geometry();
19        render_ui();
20
21        update_window();
22    }
23
24    // shutdown application
25    destroy_ui();
26    destroy_audio();
27    destroy_renderer();
28    destroy_window();
29
30    return 0;
31 }
```

Figure 15: Implementation overview pseudo code

4.3 Rendering System

The implementation of the rendering system was one of the key areas worked on throughout the project. This system is responsible for communicating with the GPU and rendering objects onto the screen. As discussed in the 2, Vulkan was the renderer API of choice.

Frames in flight Double and

64 bit world positions Shader resources SPV binary format Pipelines - Pipeline cache Pipeline derivitive Delta Time

- Matrix projection transformation (model to projection space)

4.3.1 Renderer Context

The first step in creating the renderer is initializing an object called “vk_context”. This object is created within the application that groups Vulkan handles that are responsible for initializing resources. In other words, the “vk_context” structure is used to allocate GPU resources. The handles within the context structure can be seen in the code snippet below and a diagram can be seen in figure 11.

```

1 struct vk_context
2 {
3     VkInstance           // Initializes Vulkan library
4     VkPhysicalDevice    // Handle to physical hardware
5     VkDevice             // Logical handle to physical hardware
6     VkQueue              // Graphics queue
7     VkQueue              // Presentation queue
8     VmaAllocator         // VMA memory allocator
9 };

```

The initialization of the renderer context can be broken down into several stages. The first of these states is acquiring the function pointers into the Vulkan loader which contains the implementation details for the GPU driver. This is achieved by statically linking a “stub” library file into the executable. However, as discussed in a blog post by Arseny Kapoulkine titled “*Reducing Vulkan® API call overhead*” [16], he finds that this method has some overhead due to how function calls are dispatched. To reduce this overhead, a meta-loader called Volk is used which contains pointers to the real implementation and is dynamically loaded at runtime.

The next step is acquiring a GPU with a specific set of requirements that can be used for rendering. This step involves querying all available GPUs their names, hardware capabilities as well as if it supports basic screen rendering.

4.3.2 Swapchain

- Double, Triple Buffering - VSync

4.3.3 Frame synchronization

Once the swapchain has been fully initialized, the renderer can now start creating the necessary resources required for frame synchronization. Vulkan

has two concepts that relate to synchronization which are `VkFence` and `VkSemaphore`.

```

1   struct vk_frame
2   {
3       VkFence submit_fence;
4
5       VkSemaphore image_ready;
6       VkSemaphore image_complete;
7   };
8

```

Figure 16: Frame sync structure

The Vulkan 1.3.246 specification states that “`VkFence` is a synchronization primitive that can be used between queue submissions and the host” [7.3 Fences]. In other words, a fence can be signaled on the CPU to indicate in this case, when a new image from the presentation engine has been acquired via the `vkAcquireNextImageKHR` function call.

Similarly, “`VkSemaphore` is a synchronization primitive that can be used between queue operations” [7.4 Semaphores]. For the application, this means that rendering operations can occur simultaneously for multiple frames while ensuring that frames “in-flight” are not interrupted.

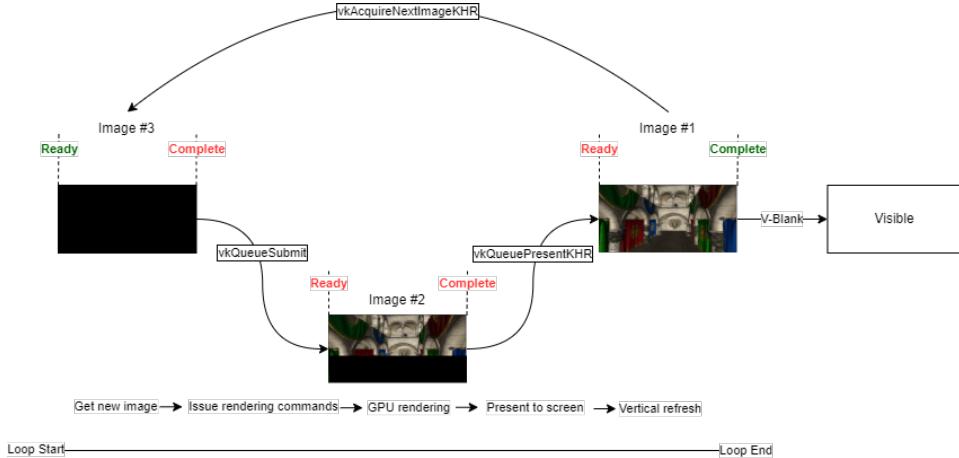


Figure 17: Frame Synchronization

4.3.4 Framebuffers

The term “Framebuffer” refers to a region of memory that stores frame data i.e pixel colors. Framebuffers are a fundamental concept in graphics rendering that stores the data for each frame.

4.3.5 Texture sampling

4.3.6 Deferred Rendering Pipeline

- Explain what forward rendering is, what deferred rendering is and how it is better

At its core, the renderer uses a deferred rendering technique which separates geometry rendering and lighting into different stages.

The key benefit of deferred rendering is increased performance

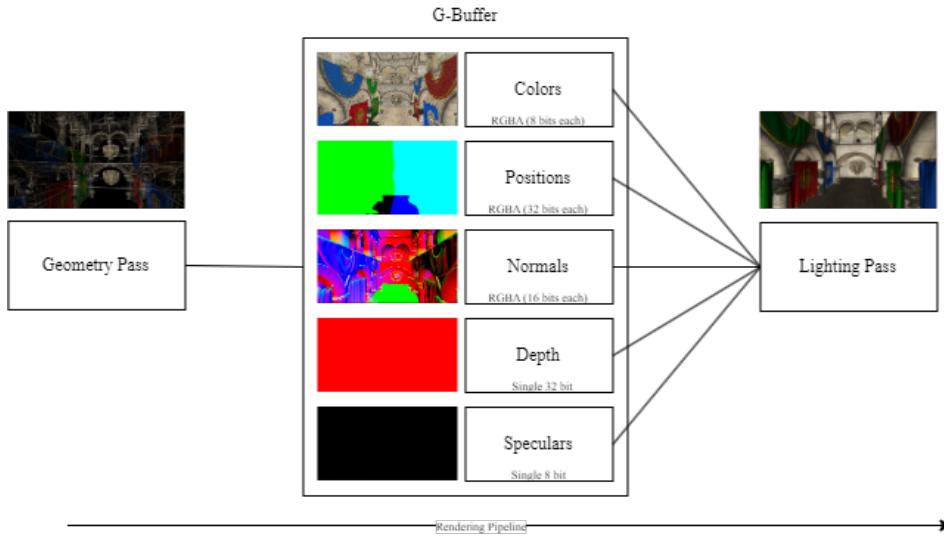


Figure 18: G-Buffer Pipeline

4.3.7 Dynamic Uniform Buffers

Uniform buffers are regions of memory located in Video Random Access Memory (VRAM) on the GPU. This memory can be accessed by shaders when creating a frame. These buffers can contain any sort of data including camera information, light properties, object transformations etc.

VMVE makes use of two dynamic uniform buffers one for the camera projection and the other for scene information such as lights. A dynamic buffer is a buffer that is large enough to store per-frame data and each frame of data can be accessed using an offset into the buffer and the current frame index. 19 shows the internal structure of a dynamic uniform buffer that stores three sub-regions of memory in a triple-buffered frame setup.

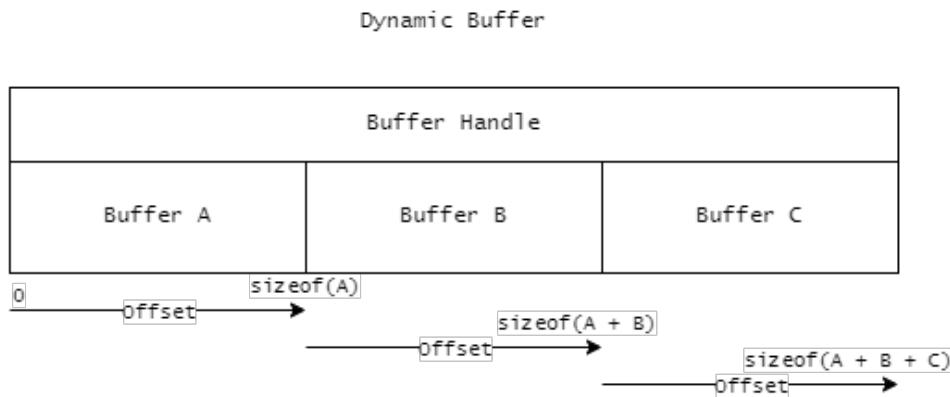


Figure 19: Dynamic Uniform Buffer

The use of dynamic uniform buffers provides several benefits compared to using a unique buffer handle for each frame.

- reduces the need to manage unique buffers, fewer state changes (binding).

4.3.8 Models

In the context of the rendering system, a “model” is a structure that represents a 3D geometry object. This could be as simple as a cube or as complex as an entire scene.

The data structure contains several key pieces of information such as geometry data and textures.

Complex models are not singular pieces of geometry. Instead, artists combine multiple smaller objects to form the final model. These smaller parts are known as “Meshes” within the application.

Figure 20 shows the internal structure of an example model which has been loaded into VMVE.

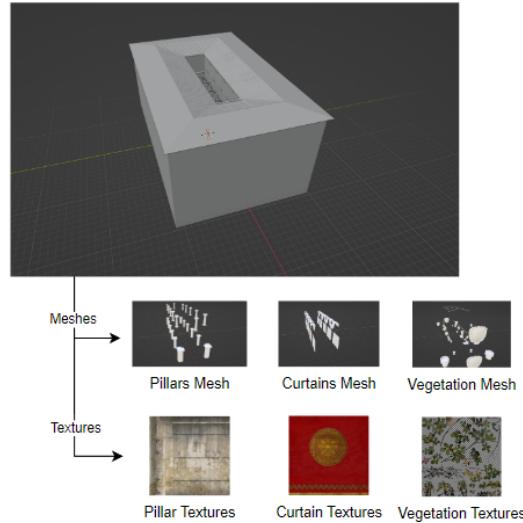


Figure 20: Model Structure

All uniquely loaded models within the application are stored in a contiguous array.

4.3.9 Entities

An entity represents an instance of the model in the virtual environment. There can be many different entities using the same model. An example of this can be seen in figure 21 which shows four entities using the same backpack model.

This is achieved by storing a model index that indicates which model the entity refers to within the contiguous array of models. Secondly, an entity contains a transformation matrix that positions the entity in the world. A more in-depth explanation of the model matrix can be found in section 4.3.10.

4.3.10 Camera

3D geometry data must be transformed through a series of mathematical calculations that will take vertex points from a 3D “world” and then convert



Figure 21: Multiple entities in virtual environment

them onto a 2D image for it to then be displayed on a monitor. This transformation is known as perspective projection [17] and is accomplished by computing several intermediate coordinate spaces as seen in figure 27.

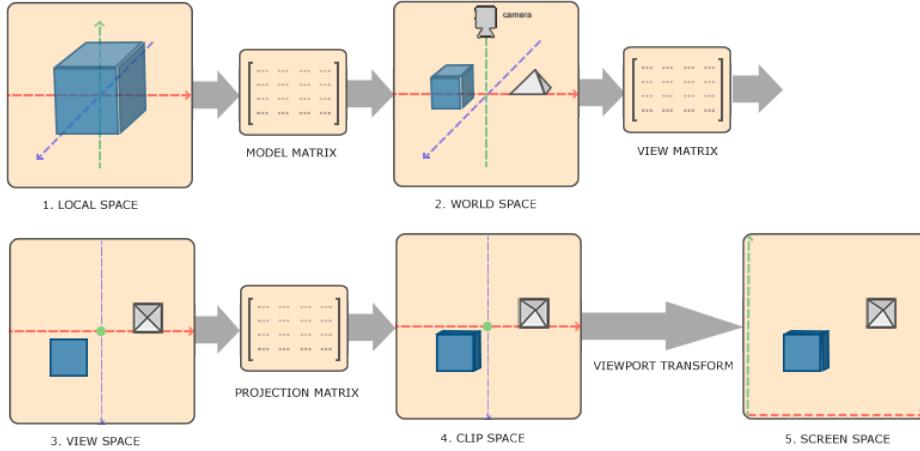


Figure 22: MVP Transformation [18]

Geometric data is first created within a local coordinate space. This “space” is positions relative to the object. In other words, the model data imported by VMVE will be in this local coordinate system often created by a 3D modeling program such as Blender or 3DSMax.

The next step is to convert these local coordinates to “world” space. This is the actual virtual environment that an object will live in. The transformation to this space is done by constructing a 4x4 matrix and performing a combination of translation, rotation and scaling. A pseudo-code example can be seen in 23.

```

1  mat4 model = mat4(1.0f);           // Identity matrix
2  model = translate(position);       // Move object
3  model = rotate(radians, axis);    // Rotate object
4  model = scale(scale);            // Scale object
5

```

Figure 23: Model matrix construction

The next step is transforming the world space positions to view space or also known as camera space. This is important as how the virtual scene is displayed depends on the properties of the camera. In the context of graphics rendering the concept of a “camera” does not exist and is only really an illusion. In reality, all points/vertex positions in the world space are transformed relative to the “camera”. For example, if the position of the camera along the z axis increases i.e. we move forward then all objects in the world will be moved towards us. A nice visualization of this is shown in figure 24 courtesy of a blog post by Jordan Santell <https://jsantell.com/model-view-projection/>.

VMVE makes use of a quaternion to perform the view projection. This is an alternative to Euler angles and has several benefits including, preventing gimbal lock and easier interpolation between orientations.

The final step in calculating the MVP matrix is the projection which converts points from local space to clip space. This involves projecting the points to either a perspective or orthographic projection.

With the fully constructed mvp matrix, this can now be multiplied with each vertex position and it will display onto the screen as expected.

A more detailed code example can be seen in figure 48 in the appendix.

4.3.11 Lighting

The lighting model that is implemented in Blinn-Phong which derives from the original Phong model developed by By Bui Tuong Phong in a paper

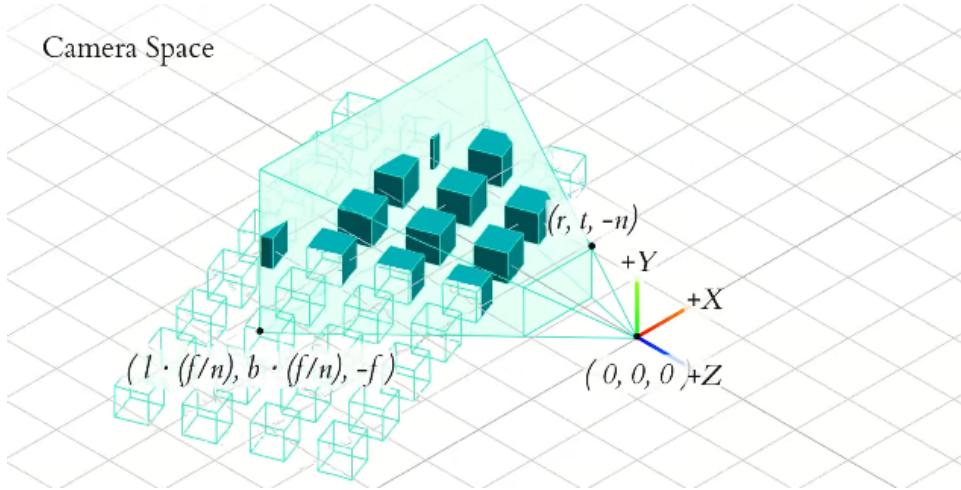


Figure 24: Camera/view projection [19]

```

1     mat4 view = lookAt(camera_position, view_direction,
2                           camera_up);

```

Figure 25: View matrix construction

published in 1975. Purpose of lighting model is to calculate approximations of lighting based on the real world. [20]

Ambient is a constant value that is used instead of global illumination as it requires more computational resources and more complex algorithms.

$$A = G + P \quad (2)$$

The next step is implementing diffuse lighting. This takes into account the light direction L and the normal N for a surface at a particular pixel. The formula below calculates the intensity at which light reflects off the of an object based on the angle the surface is against a light source.

The dot product of the light direction and surface normal returns a value between the ranges of -1 to 1 depending on how parallel the directions are. If this value is less than 0 then it's clamped as a result of the max function

```

1     mat4 proj = perspective(fovy, aspect, near, far);
2

```

Figure 26: Projection matrix construction

$$Output = MVP \times Vertex \quad (1)$$

Figure 27: MVP projection

which returns the largest value for the given two parameters.

$$I = \max(\vec{L} \cdot \vec{N}, 0) \quad (3)$$

$$(4)$$

Having calculated the intensity value we can now simply multiply it with the objects surface colour.

$$D = I \times C \quad (5)$$

Figure 28 demonstrates the use of diffuse lighting which shows how each surface of the cube is lit differently based on its angle to the directional light source.

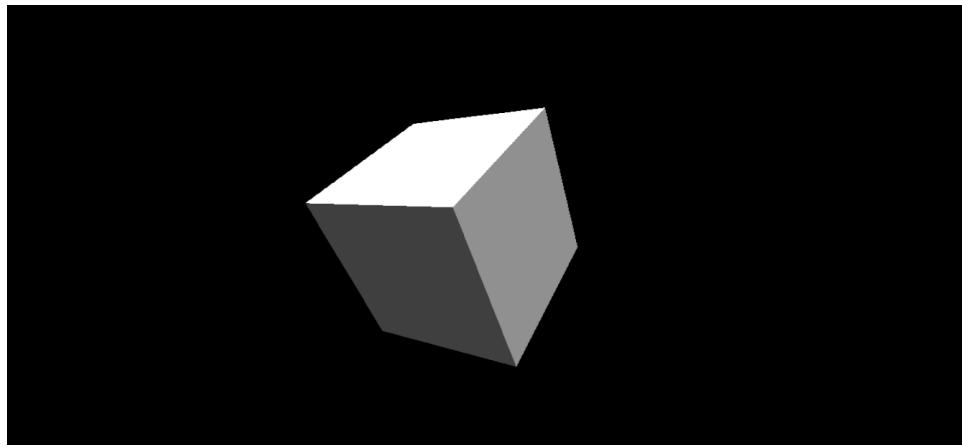


Figure 28: Diffuse Lighting

The final step in the Blinn-Phong lighting model is specular highlighting. This effect adds...

4.4 User Interface

The implementation of the user interface was the next major system. This is the frontend and how the users will be able to interact with the application. The user interface is built on top of the Vulkan renderer.

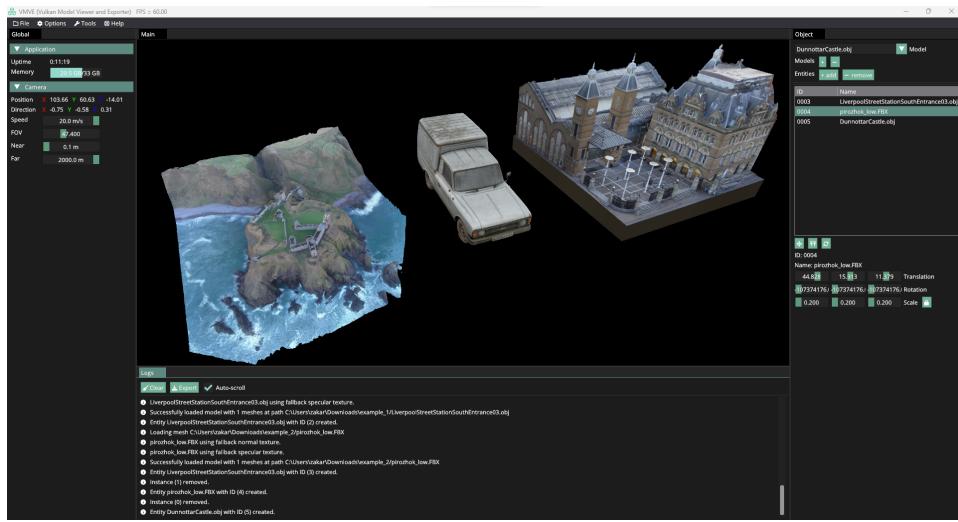


Figure 29: UI implementation

4.4.1 Controls

The term “Controls” refers to a combination of keys also known as “Shortcuts” that are used to perform specific actions within the application. There are various built-in controls that aim to increase the productivity for the user by reducing the amount of clicking and menu interaction for repeating tasks.

Controls are split into two categories which are Global and Viewport. Global controls are controls that can be activated at any point. Viewport controls however, can only be activated whilst using the viewport i.e the camera.

This distinction for controls between different modes allows for greater context and better usability.

4.4.2 Fonts and Icons

The font used for the user interface is Open Sans which provides a simple and easy to read font.

VMVE also uses icons throughout the user interface and is an important aspect in conveying key information such as the task being performed or for additional information. The icon font used is provided by Font Awesome [21].

Typically, data for fonts and icons are stored in a font file which end using extensions such as “.ttf” or “.otf”. However, one of VMVEs goals is to be distributed as a single executable file. Therefore, we cannot depend on external font files. Instead, data for fonts and icons are stored directly in the application in a continuous array of bytes and are encoded in base85. An small example of what this looks like can be seen in figure 30. The full version of this is over 3000 lines long due to the vast of amount of data stored within the font.

```

1 // 206 out of 201650 characters are shown
2
3 const char open_sans_regular[201650 + 1] =
4 "7])#####2Pc7('/##I),##d-LhLjKI##4%1S:'*]n8)K.v5*8_c)iZ
;99=$$$$_c(m]4pKdp/(RdL<snZo'oI,hLNnx4Uu/>8Q7oo^eFb3hB4JYc'
Tx-3l_wgd2Tf._r+&sAqV,-G"" :F8LD=5,n]A&aA+<gXG-<iobW&>$>QJ8Z
.W$jg0Fv-o^(^JJnf4T"
5

```

Figure 30: Base85 encoded font

4.4.3 Menu Bar



Figure 31: Menu Bar

4.4.4 Load Model Window

The load model window is accessed through `File > Load Model` or by pressing the `ctrl + L` shortcut. This window allows the user to load a 3D model at runtime by traversing the file system and selecting a model to load.

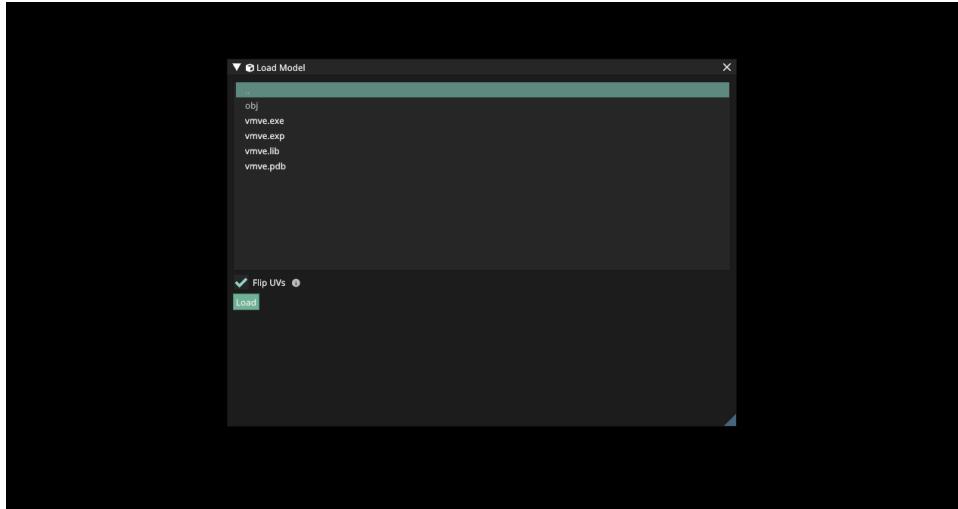


Figure 32: Load Model Window

4.4.5 Export Model Window

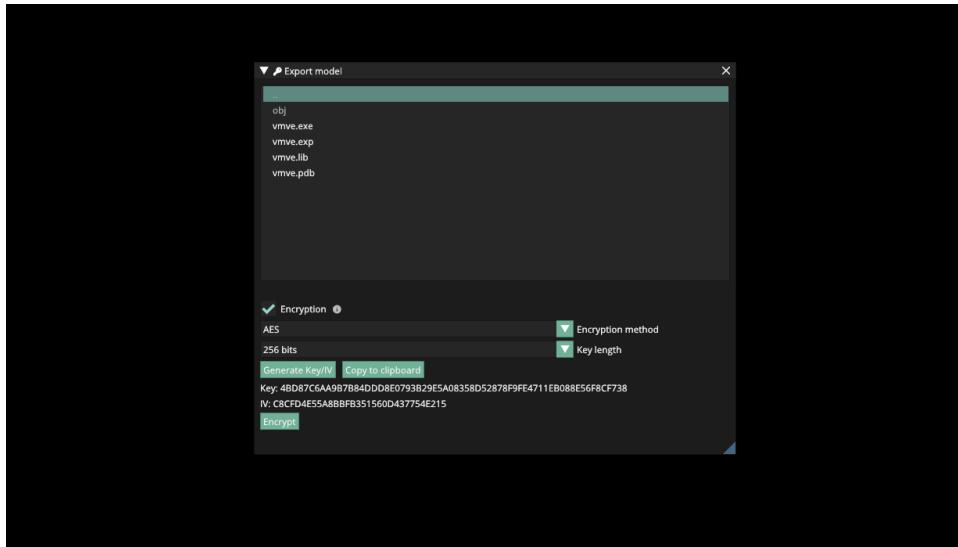


Figure 33: Export Model Window

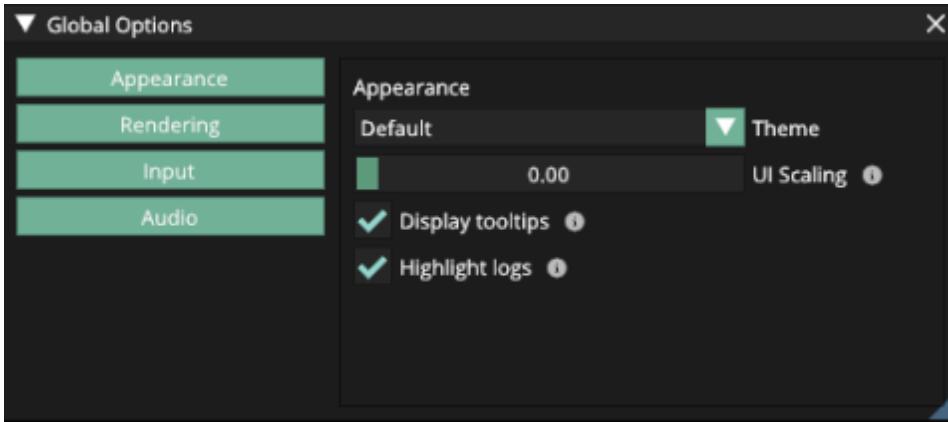


Figure 34: Settings Window

4.4.6 Settings Window

4.4.7 Object gizmo

An additional feature that is part of the user interface is the gizmo. This is a visualization of one of three operations that is the main method of interaction that a user has with an object and is used to specify the exact location and orientation within the virtual environment. The operations are translation (moving), rotation and scaling and can be seen in figure 35 respectively.

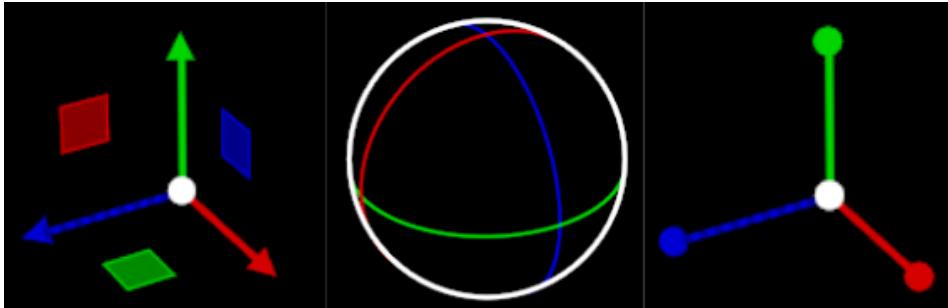


Figure 35: Gizmo operations

This functionality is implemented by taking the matrix transformation of an object and feeding that information to ImGuizmo [22]. It will then perform the necessary mathematical calculations to convert from the objects

world space to screen space. In other words, no matter where in the virtual environment the object is located, it will always be shown relative to the users screen. A small code snippet can be seen below 36 where M represents the model in the MVP projection.

```

1   const auto& operation = static_cast<ImGui::OPERATION>(
2     guizmo_operation);
3   const auto& mode = ImGui::MODE::WORLD;
4   ImGui::SetDrawlist();
5   ImGui::SetRect(x, y, viewport_x, viewport_y);
6   ImGui::Manipulate(view, proj, operation, mode, m);

```

Figure 36: ImGuizmo world to screen space

4.5 Logging system

Due to the relative complexity of the underlying application and number of moving components a logging system was developed to provide a clear understanding of the current state of VMVE.

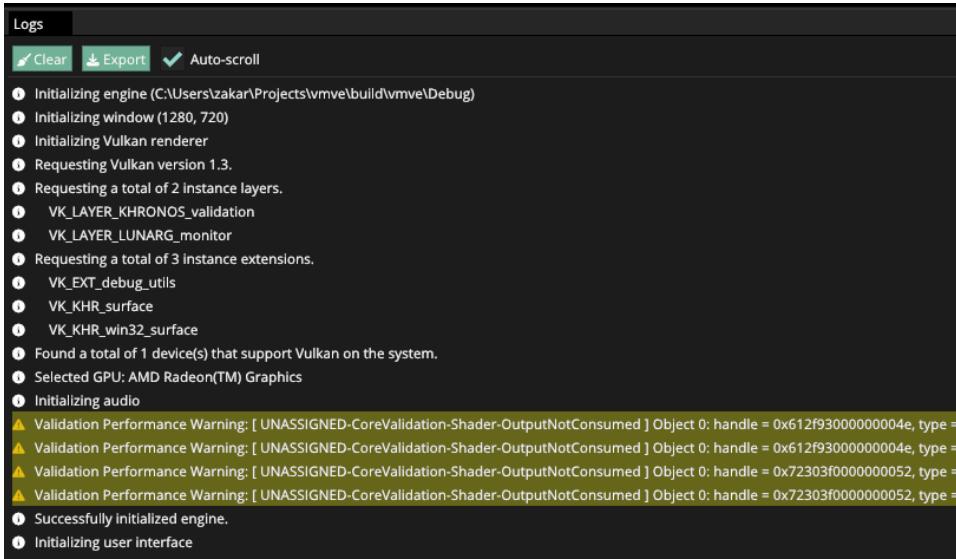


Figure 37: Logging window

Messages are stored in a fixed-size array that is preallocated. This ensures that there are no potential allocations occurring each time “print_log” is

called. By default VMVE allows for a maximum of 10,000 log messages before the buffer becomes full. In the event that the buffer does become full, the first log message i.e the oldest one is overwritten when a new log message is created 38.

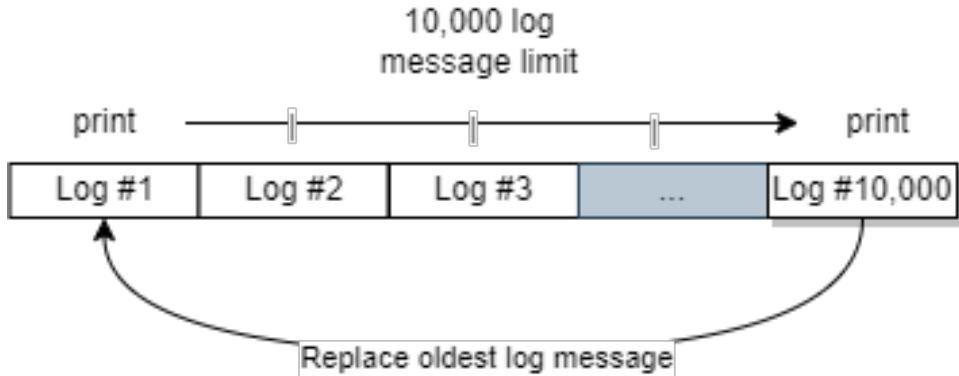


Figure 38: Logging FIFO system

4.6 Encryption and custom System

- AES (key and initialization vector) – Image of how the system works – Loads model file, encrypts it and then writes it back out

4.7 Custom File Format

- File Format structure

4.8 Distribution

- Release mode (optimized) - Runs on multiple systems - Windows only currently

4.8.1 Versions

VMVE follows the major, minor and patch system of versioning and is used as follows [Major].[Minor].[Patch]. The use of versions is important in differentiating between VMVE releases. Each new version of the application comes with new features as well as bug fixes that aim to improve the software over time. Due to the rapid development of new features and functionality, backward compatibility cannot be guaranteed. The current official release of VMVE is v0.0.4.

4.8.2 Website

Alongside the application, a website was created as a platform for easily distributing the application. It includes a features section that showcases and gives users a preview of the application through the use of images and videos. Furthermore, a download link is provided giving users an easy way of obtaining the executable without needing to understand the technicalities of GitHub as it is designed with programmers in mind.

In regards to downloads, there are two types. The first is an active development version which is regularly updated and acts as a beta release for versions that have not yet been officially released. The second is current and past VMVE versions going all the back to the first official release (v0.0.1).

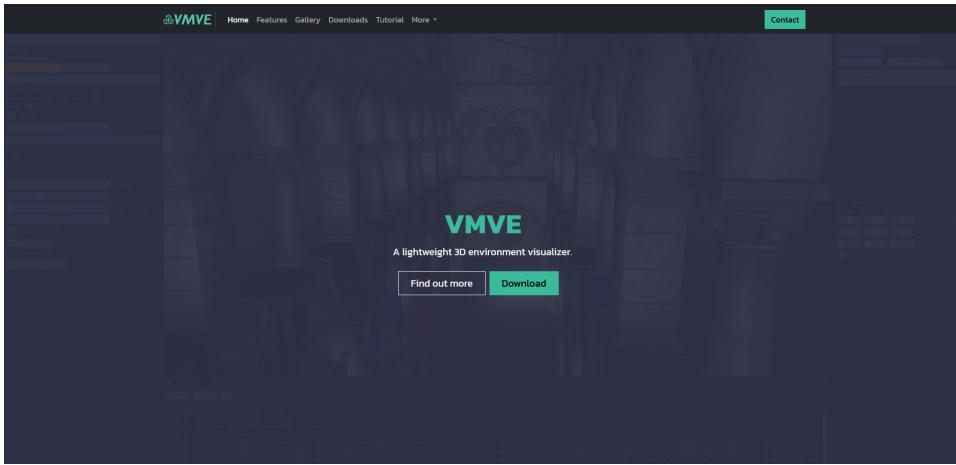


Figure 39: VMVE website

4.8.3 Example models

The VMVE website provides an additional download link to six different example models. These are provided by third parties (with appropriate credits) and are corrected to ensure they can be loaded into VMVE without any issues. The purpose of these example models is to allow users to easily test the application without needing to search the internet or create their own.

4.8.4 Documentation

In addition to a website, a documentation website was also created courtesy of Read the Docs (<https://readthedocs.org>). The purpose of this site is to provide additional information about VMVE and also, provide an in-depth tutorial that aims to help users understand how to use the application.

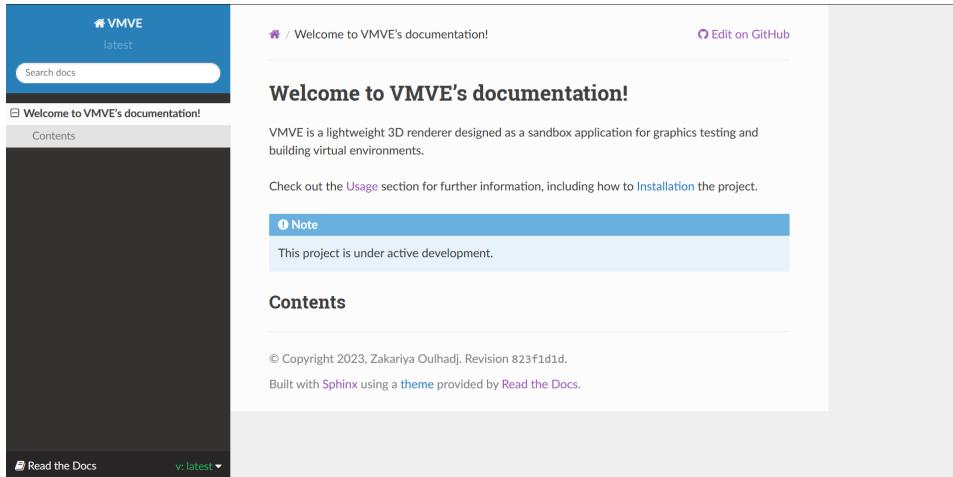


Figure 40: VMVE documentation

5 Evaluation

The completion of the project transitions into the evaluation stage where the project is evaluated against the original goals and requirements in order to judge if those requirements have been met. When evaluating the project there are two distinct categories. The first is self-evaluation and the other is user feedback.

5.1 Distribution

In hindsight, the most challenging aspect of the entire project was by far, distribution and more specifically ensuring that VMVE was able to run on all supported systems as expected. Throughout the applications development, there were points where VMVE would work on the development machine, however, throw an exception error on other systems. These inconsistencies paired with the lack of reproducibility made these issues quite difficult to debug. The majority of these inconsistencies between different

systems occurred during the initialization stages. This would include creating the window, initializing the renderer, initializing the UI, creating the audio system etc.

Some examples of these inconsistencies include the application crashing when resizing the window, crashing if audio is disabled on a system as well as frame stuttering.

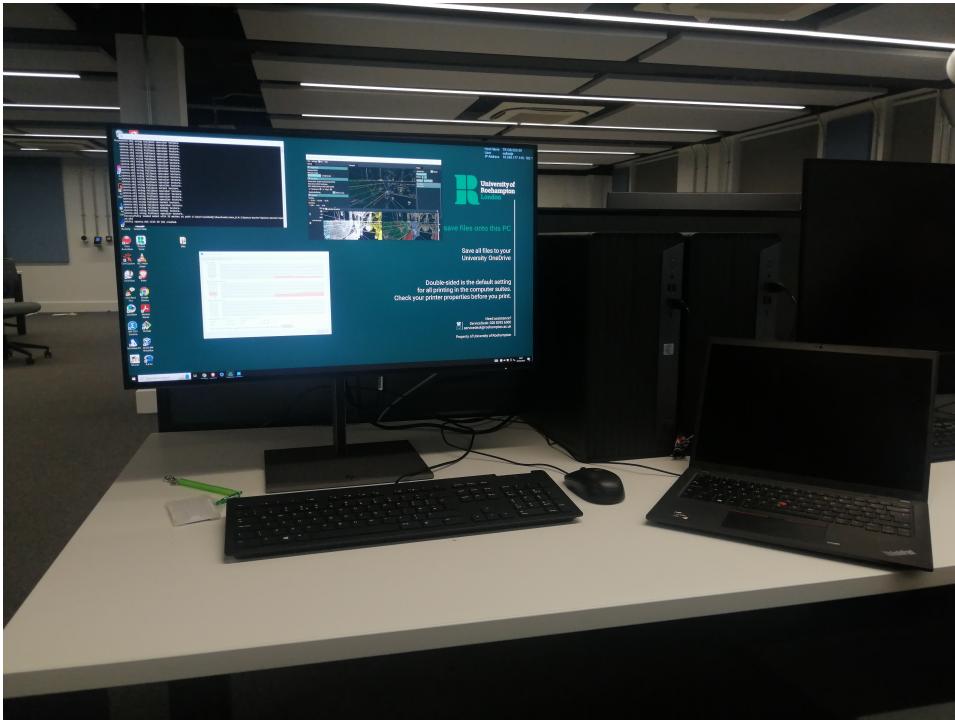


Figure 41: Working on distribution

- Redesigned logging system to take crashes into account by creating crash logs and then using this to find out exactly what error was being printed.

5.2 Programming language

- Functional style - C++ 23 - Checking for error codes first programming style

5.3 Time Management

Managing the work distribution was a vital aspect in ensuring all of the necessary requirements of the project could be met on time. Failure to correctly manage this workload would result in key goals not being achieved and/or features not being implemented.

The use of GitHub issues was highly effective in managing the projects constantly changing requirements especially as the project grew in size.

Throughout the project, over 50 GitHub issues were resolved

- How effective was the use of project management tools during development.
- Key stages of the project - Initial core systems/graphics development stage
- System redesign - Encryption development stage

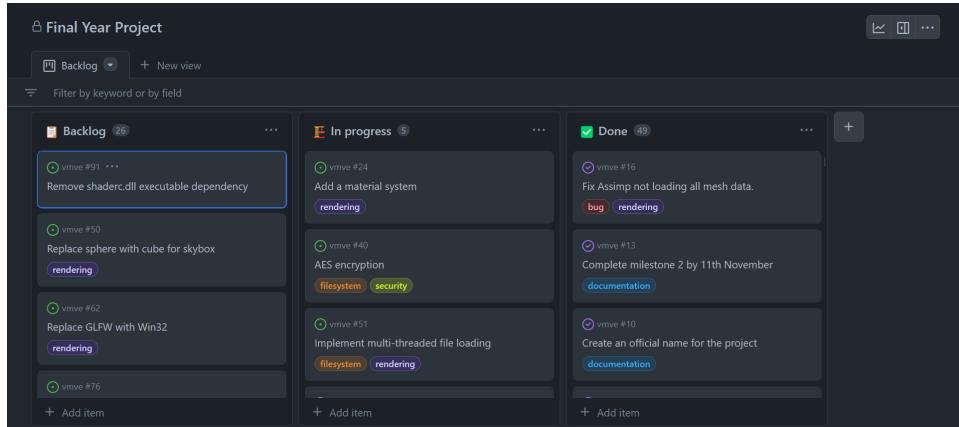


Figure 42: GitHub Issues Kanban

5.4 Performance

Measuring the performance of VMVE is another key aspect of evaluation that ensures the original goals and requirements have been met. There are two main aspects that can be measured which is compilation and runtime performance.

“Compilation” refers to the process of building the application in an offline setting. The speed at which the project is compiled directly affects the developer and subsequently the development of the project.

“Runtime” refers to the applications performance while it is running and its

effects to the end users.

5.4.1 Compilation Performance

Col1	Debug Full	Debug Partial	Release Full	Release Partial
1	6	87837	787	123
2	7	78	5415	123
3	545	778	7507	123
4	545	18744	7560	123
5	88	788	6344	123

Table 1: VMVE compilation performance

As the codebase for VMVE grew in both size and complexity, ensuring that compilation times were reasonable was a vital aspect that had to be take into consideration.

The main technique used for reducing compilation times was making use of a Precompiled Header (PCH). This is a header file (pch.h) that includes various header files such as those from the standard library as well as external dependencies that are not indented to change often. The compiler compiles this file once and is reused across compilations. This significantly reduces the amount of work the compiler needs to perform since it does not have to recompile the same sets of files needlessly each time.

The way that this works is by including the “pch.h” header file at the top of each translation unit (.cpp file) and before any other header file. This ensures that the necessary types can be found for both a header files and its corresponding source file.

5.4.2 Runtime Performance

CPU timing C++ comes with the `<chrono>` library which provides `std::chrono::high_resolution_clock`. This is a GPU timer that can record and measure differences in time using different time units such as nanoseconds, milliseconds, seconds etc.

Visual Studio IDE Performance Profiler

- Benchmarking CPU timing GPU timing
- Frame times - Startup time - no pipeline cache vs pipeline cache - pipeline derivatives - Shutdown time

Metric	Debug	Release	Col3
Initialization	6	87837	787
Update Loop	7	78	5415
Shutdown	545	778	7507

Table 2: VMVE runtime performance

5.4.3 Hardware

These tests were performed on the main development machine used throughout the project which was a Thinkpad T14s Gen 3. A follow list of the laptops specifications can be seen in the figure 3.

Component	Type
CPU	AMD Ryzen 7 Pro 6850U
GPU	Integrated
RAM	32GB DDR6

Table 3: Development Machine

5.5 User Feedback

Having conducted my own evaluation, it is equally important to obtain feedback from the stakeholders including users.

The users that tested the application were predominantly other students. The process of obtaining this feedback was separated into two stages.

The first was to measure how intuitive the user interface is which was achieved by giving a user a set of instructions such as loading a model, encrypting assets, configuring the application etc. A score would be given for each task based on how easily the user was able to complete it.

The second stage would obtain direct feedback from the users by presenting a series of questions that would assess VMVEs usability, performance and overall user experience.

This data was recorded into a spreadsheet and further analyzed to produce different sets of visualizations the first of which can be seen in figure...
TODO

6 Related Work

Computer graphics is a large field - Others who have done the same. - How good is my work compared others given the time constraints

7 Reflection

One of the major downsides that this project suffers from is the projects time constraints. Given the relative complexity of the project many of the features implemented in VMVE are quite rudimentary and serves as a basic prototype that showcases the underlying technology and the potential future work that can be undertaken.

- Learn a lot in terms of solving problems - Patience Could have planned better by designing systems before implementing them.

7.1 Choice of rendering API

This project was built on top of the Vulkan which as previously discussed is a low-level GPU API. One of major downsides to having chosen Vulkan as the API of choice for this project was the significant amount of time had to be spent implementing the various rendering features due to how verbose and technical the API is. The use of the API is only really beneficial if a developer wants to make full use of the additional performance through the use of multithreading, multiple command buffers and very specific memory allocation requirements.

If given the choice, I would rewrite the renderer, using a far simpler API such as DirectX11 or OpenGL as they provide same functionality but with significantly less work required. This would allow me to focus and spend more time implementing the many other features required in such an application.

7.2 Development logs

At key stages of the projects development, development logs i.e. videos were recorded showcasing the state of development at that specific point in time. All videos were uploaded and are hosted on the Zakariya Oulhadj YouTube channel <https://www.youtube.com/@ZOulhadj>

8 Future Work

Going forward there are various features that are currently being evaluated as potentially implemented in the near future. These features aim to greatly increase VMVEs usability and provide a whole host of new features.

8.1 Rendering

8.1.1 Multiple rendering APIs

VMVE currently only supports one rendering API which is Vulkan. As discussed in the technology review section, Vulkan is officially supported on Windows, Linux and macOS (through MoltenVK). However, in order to support additional operating system as well as hardware that does not support Vulkan, more rendering APIs should be supported including DirectX12 and previous generation APIs such as OpenGL and DirectX11.

- Graph for showing how APIs can be changed during compilation

8.1.2 Frustum Culling

Currently, VMVE sends all object data to the GPU to be process and rendered. The GPU then subsequently traverses each vertex in order to figure out if it needs to be “discarded”. This process is part of the graphics pipeline and occurs for each vertex. As the complexity of both the scene and the objects themselves increases, this starts to become a GPU intensive task and results in increased GPU usage and lower performance.

To solve this, frustum culling must be implemented which is a rendering optimization in which objects not visible from the “cameras point of view” are discarded completely and not sent to the GPU entirely. The term “frustum” refers to the camera projection frustum which can be seen in figure 43 and “Culling” simply means discarding.

This technique significantly improves performance as each object in the world is contained within a “bounding box” which is often a cube or a sphere 44. Then for each object, a check is performed against the bounded box instead of the actual vertices. This allow for in the best case a single check or at its worst 8 checks per object. This is far better than needing to perform thousands of checks for all the vertices of an object.

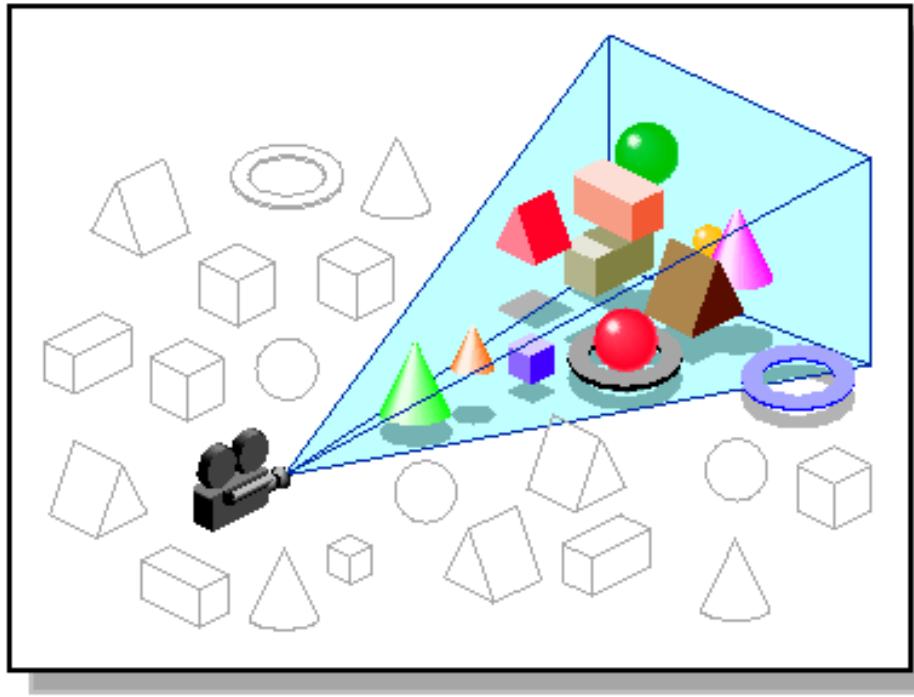


Figure 43: Frustum Culling [23]

8.1.3 Spatial Acceleration Structures

VMVE only supports loading basic models however, in the future many other features need to be implemented. One such feature is large scale terrain as seen in figure 45.

Currently, VMVE would struggle to render such objects due to its complexity in terms of the number of vertices required. For example, an area of 20x20km with a resolution of 1 meter would require 400 million vertices. Each vertex, if packed efficiently could be 32 bytes each that includes positions (12 bytes), normals (12 bytes) and texture coordinates (8 bytes). In terms of memory, this would require 12.8GB of data just for the terrain.

A common solution to this, is implementing a type of spatial acceleration structure also known as Level of Detail (LOD). These structures are designed as the name suggests, to increase the speed for algorithms in the spatial domain including images and environments.

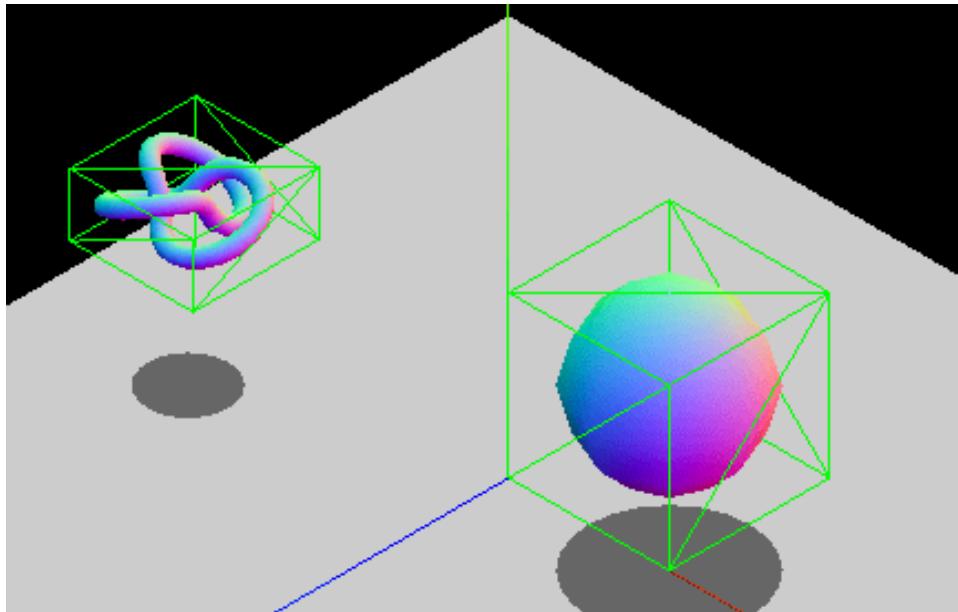


Figure 44: Bounding Boxes [24]

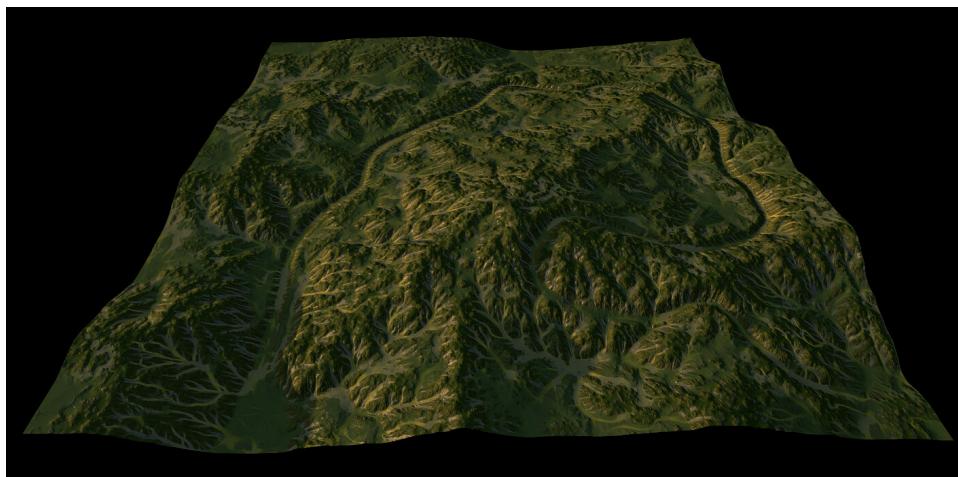


Figure 45: Large scale terrain

A quad tree is a type of spatial acceleration structure which stores a hierarchical collection of nodes that each represent a 2D area (and an octree in the case of 3D). Figure 46 visualizes a quad tree that shows the resolution

of each tile and how there are fewer tiles the further away from the camera they are.

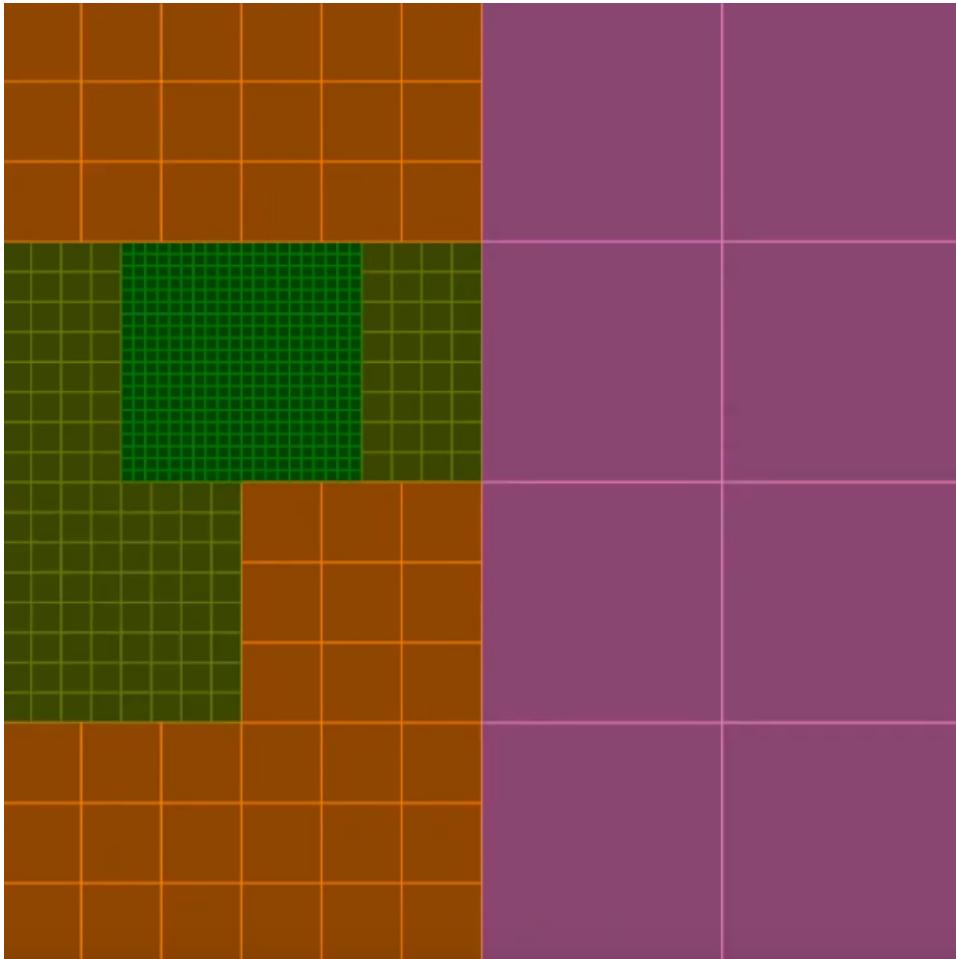


Figure 46: Quad Tree visualization

The benefit of using this technique is that the number of vertices are significantly reduced saving on performance and memory usage.

8.1.4 glTF Support

Currently, the engine only really supports the VMVE and OBJ model formats for importing. The main issue with the OBJ file format is its size since the data is stored in a text format which subsequently increases the

assets file size. glTF [25] is a new model format by The Khronos Group that has many useful features such as compression, binary representation, scene hierarchy and more.

8.2 Cross Platform

Windows is the only operating system that VMVE officially supports. Implementing cross platform support would greatly benefit the application as it would increase flexibility in terms of which systems its able to run on and subsequently, increase the potential user base. Implementing such functionality would require significant changes to the underlying architecture of the application such as implementing opaque types for structures that have a different implementation depending on the operating system being used.

Additionally, a different build system has to be used that is cross platform. The most commonly used cross platform build system is CMake [26].

8.3 Networking Support

VMVE is a virtual environment editor and as such can be significantly improved by adding support for networking. The idea is that there would be a server running which would keep track of the virtual world and multiple clients via VMVE would be able to connect and interact with the environment simultaneously.

This would allow for greater efficiency and speed up various tasks.

8.4 Encryption

VMVE supports both AES and Diffie-Helm encryption algorithms out of the box. Additional work should be carried out to add more algorithms such as.....

8.5 Version Control

In regards to the VCS (version control system) architecture, a potential change that can be done is to add a third branch called “Beta”. The purpose of this branch would be release relatively stable but yet unfinished features to users. This would allow user to use new features and test them before an official version is released. Overall this would reduce the number of bugs in final versions and be beneficial to users who are keen in using recently

developed features. Figure 47 shows how the VCS architecture could look like with the addition of a “Beta” branch.

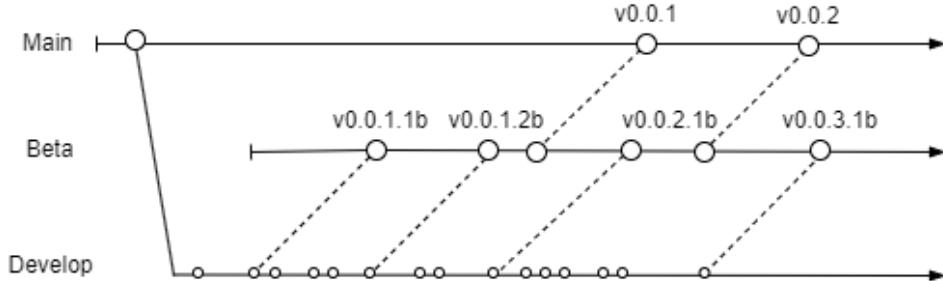


Figure 47: Potential future git branch design

8.6 Reduce library dependencies

VMVE makes use of several libraries which allows specific functionality to be added quickly. This is ideal given the projects time constraints and requirements. However, going forward the aim will be to reduce the number of external libraries being used.

This will provide various benefits such as less reliance of external code and therefore, more control, smaller

- Replace libraries with a custom solution – Lower footprint as only the required features are implemented.

8.7 Accessibility

Another aspect that needs to be addressed soon is improved accessibility. The application includes some features that address this such as icons, a tutorial, documentation as well as additional information. However, some of the features that VMVE does not include is taking into account color blindness and text-to-speech. The reason for this is that these are more complex topics and required additional time and research to ensure a proper implementation is released.

Another task that must be considered is localization. VMVE only supports the English language and has no way of adapting to other languages. Therefore, the internal structure of the application must be redesigned to allow for other languages to be added and thus, improving accessibility.

9 Conclusion

VMVE has been designed to be a platform in which users are provided easy to use 3D graphics tools without needing to know the complex details that come with that. This allows users to worry less about technicalities and more about their specific needs and requirements when using VMVE.

This has been a long journey that has presented me with various challenges throughout the development of VMVE.

Glossary

Vulkan Low-level GPU application programmable interface. 10, 11, 12, 23,
55

Acronyms

API Application Programmable Interface. 7, 10, 11, 43, 55

CPU Central Processing Unit. 6, 7, 23, 41

GPU Graphics Processing Unit. 7, 8, 9, 10, 11, 21, 22, 24, 41, 43, 44, 54, 55

IDE Integrated Development Environment. 6

IP Intellectual Property. 3

LOD Level of Detail. 45

MSVC Microsoft Visual Compiler. 6

PCH Precompiled Header. 41

STL C++ Standard Template Library. 9

VCS Version Control System. 5

VMVE Vulkan Model Viewer and Exporter. 1, 2, 3, 4, 6, 10, 11, 12, 15, 16, 19, 20, 25, 27, 28, 32, 35, 36, 37, 38, 40, 41, 42, 43, 44, 45, 47, 48, 49, 50, 54, 55

VRAM Video Random Access Memory. 24

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11 Appendices

11.1 Rendering API history

One of the core aspects of VMVE is making use of the underlying hardware and more specifically the GPU (Graphics Processing Unit) which will be primarily used for rendering. Taking advantage of the GPUs hardware capabilities requires low-level access to the hardware and is not as straightforward as one would hope. To understand why, we must first understand how Graphics Processing Units function.

There are different types of GPUs such as dedicated or onboard, different architectures including AMDs RDNA [27] or NVIDIAAs ADA [28] as well as various capabilities that differ between hardware vendors. An application attempting to target GPUs would need to consider this including having access to the GPU drivers (Low-level software that allows a specific piece of hardware to function). Oftentimes, drivers are considered trade secrets that companies do not want freely available. Given the complexity and variations of modern GPUs this is simply not feasible.

Companies from across different industries solved this issue by creating an open, non-profit consortium in the early 2000s called The Khronos Group. This organization develops, publishes and maintains standards for different areas but most notably for 3D Graphics and Computation. Companies follow these standards when developing software allowing for interoperability across hardware. As of 2023, The Khronos Group actively maintains 16 different standards. Out of all those standards, there are two which are the most suitable for VMVE, OpenGL and Vulkan.

OpenGL and Vulkan are two types of rendering APIs that are designed based on The Khronos Group specifications. When attempting to provide graphics support for a particular GPU, hardware vendors follow the OpenGL and/or Vulkan specifications when implementing their drivers. For applications, a Application Programmable Interface (API) is provided allowing for direct control of the GPU.

VMVE could support both OpenGL and Vulkan however, due to the vast amount of work required to accomplish this as well as the project's time constraints this is simply not feasible. Instead, both need to be evaluated to choose one.

11.2 Camera transformation code

```

1 // Construct M (model)
2 glm::mat4 m = glm::mat4(1.0f);
3 m = glm::translate(m, world_position);
4 m = glm::rotate(m, radians, rotation_axis);
5 m = glm::scale(m, scale_amount);
6
7 // Construct V (view)
8 glm::mat4 v = glm::lookAt(camera_position, camera_direction,
9 , camera_up);
10
11 // Construct P (projection)
12 glm::mat4 p = glm::perspective(field_of_view, aspect_ratio,
13 near, far);
14
15 // Construct MVP
16 glm::mat4 mvp = p * v * m; // Order is important

```

Figure 48: Complete MVP example