



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. It is intended to serve as an important application that bridges the gap between new users and industry-leading rendering engines.

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.

May 8, 2023

Date

z. oulhadj

Signature

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Glossary

CL The Microsoft C compiler and linker.

Vulkan Low-level GPU application programmable interface.

Acronyms

API Application Programmable Interface.

CPU Central Processing Unit.

GDPR General Data Protection Regulation.

GPU Graphics Processing Unit.

IDE Integrated Development Environment.

IP Intellectual Property.

LOD Level of Detail.

MSVC Microsoft Visual Compiler.

OS Operating System.

PCH Precompiled Header.

STL C++ Standard Template Library.

SVN Apache Subversion.

UI User Interface.

VCS Version Control System.

VMVE Vulkan Model Viewer and Exporter.

VRAM Video Random Access Memory.

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 a wide range of 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 and consists of various benefits that computer graphics provide to the real world.

1.1 Project Problem

Industrial graphics software today are large and highly technical applications that are the culmination of decades worth of work. Examples include Unreal Engine^[1], Unity^[2] and RenderMan^[3]. These applications provide users with cutting-edge technology such as ray tracing, real-time global illumination, subsurface scattering, geometry compression, streaming and much more that are designed for use in professional environments which results in stringent requirements and complex feature sets.

This results in the adoption of the software being a barrier to entry for graphics developers, artists and businesses which inadvertently introduces a wide range of issues such as requiring training for employees, additional costs for businesses and a decrease in productivity. Other issues include performance, compatibility and storage when using these complex applications.

To address these issues, I introduce my final year project, Vulkan Model Viewer and Exporter (VMVE). A standalone application developed in the domain of computer graphics that provides an easy-to-use, efficient platform for 3D graphics rendering and asset encryption. It will also serve as an important tool and as a stepping stone that aims to bridge the gap between new users and industry-leading rendering engines.

To achieve this, VMVE will provide a small but specific subset of features that are designed from the ground up to be easy to use and understand for rapid graphics prototyping such as constructing virtual environments, simulating the effect of light on 3D geometry and securing digital assets through the use of encryption.

1.2 Stakeholders

Stakeholders are individuals or groups who have an interest or "stake" in VMVE which can include decisions made throughout the development or

the end product. Each stakeholder group may have different goals, priorities, and expectations, which can sometimes lead to conflicts and challenges in decision-making and implementation. It is important to identify the different groups to ensure their requirements and concerns are being taken into account so that informed decisions can be made.

1.2.1 Students and trainees

Students and trainees are the key stakeholder groups for the project which the application will be designed to accommodate by providing the necessary tools and functionality. This includes providing a suite of easy-to-use tools for graphics rendering that students and trainees could use to learn about basic rendering concepts and to use this knowledge to construct virtual environments for graphics prototyping and rendering.

1.2.2 Businesses

The other type of stakeholder is employers who will want to train new potential employees in the field of computer graphics. The goal is for businesses to use VMVE as a training tool to lower the learning curve and reduce the barrier to entry within the graphics industry.

1.3 Requirements

The design, implementation and evaluation of the project rely on a set of aims and objectives to be fully defined. The first step toward obtaining these requirements requires a “requirements gathering” stage. The purpose of this is to outline and better understand the requirements for each of the stakeholders mentioned in the previous section.

1.3.1 Aims

VMVE has several aims which outline the general goals that the application wishes to provide.

- 1. Virtual environment rendering** The first aim of VMVE is to provide an “easy-to-use” platform for creating virtual environments. This means that the application should reduce the learning curve so that users with little to no prior experience with 3D rendering software and the underlying technology such as students and trainees can use the application to achieve their desired goals.

2. **Lower system requirements** The second aim is to focus on the efficiency of the application to lower the hardware requirements.

The efficiency and aims vary based on the component in question that include the Central Processing Unit (CPU), Graphics Processing Unit (GPU), memory and storage. From the ground up VMVE will strive to be as efficient as possible by using the latest technologies available.

3. **3D asset encryption** The last of the three main aims is for the application to include a custom model format that makes use of encryption to safely secure a user's digital assets. The motivation for this functionality formed as a result of the increase in theft regarding digital assets. A recent example relates to the recent data leak that affected Rockstar Studios and their upcoming game (Grand Theft Auto 6) that saw assets, source code and documentation released to the public^[4].

1.3.2 Objectives

The objectives are concrete requirements that need to be implemented in order to achieve the aims outlined in section 1.3.1.

1. **A platform for virtual environment rendering** The project will be built to run as a desktop application that renders a user interface editor as well as a virtual environment. The User Interface (UI) must be designed intuitively and reduce the amount of friction between the application and the user's 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.

2. **Lower system requirements** This can be achieved through the use of efficient algorithms and technologies related to rendering that will allow for assets to be displayed using as little hardware resources as possible. For example, by using the latest rendering Application Programmable Interfaces (APIs) and packing/compressing crucial data.

3. **3D asset encryption** 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 in tandem 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 into the application.

With these aims and objectives fully defined, the project proposal document was signed off as part of the requirements for milestone 2.

Student and First Supervisor Project Sign Off

STUDENT: I agree to completing this project:	<input checked="" type="checkbox"/>	Date:	10	/	11	/	22
Student Name:	Zakariya Oulhadj						
Student Signature:	Z.Oulhadj						
<hr/>							
SUPERVISOR: I approve this project proposal:	<input checked="" type="checkbox"/>	Date:	10	/	11	/	2022
Supervisor Name:	Dr Charles Clarke						
Supervisor Signature:							

It is the supervisor's responsibility to approve this project as meeting the requirements for the module. This includes professional body requirements, programme requirements, and module requirements. By signing the form, you are agreeing that you have validated the suitability of the project.

Figure 1: Project proposal sign-off

1.4 Considerations

Several different types of considerations must also be taken into account before commencing work on the application.

1.4.1 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.

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

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 initialisation 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.

No modification to geometry

No data is send or received

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.

As the application does not store or process any personal information, General Data Protection Regulation (GDPR) has not been taken into consideration. In the future, however, if the use of data and information changes then this will be revisited to ensure that all laws are adhered to.

1.4.2 Social

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

Accessibility is a vital aspect that needs to be addressed throughout the

development to ensure the application is useable for those with disabilities.

1.4.3 Ethical

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.

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.

1.5 BSc Justification

The development of VMVE is an ambitious and challenging project that requires a strong understanding of computer graphics, programming, and software architecture. This project is a large undertaking that uses the skills and knowledge gained through the BSc (Bachelor of Science) computer science program from modules such as software development (1, 2, 3), algorithms, data science and mathematics. It not only showcases technical ability but also highlights critical thinking, problem-solving, decision-making and time management skills.

As such, they will be highly valued in the professional industry and necessary for success in the field of computer science and therefore, is a suitable choice for a final-year project.

1.6 Overview

This report is structured such that it presents each aspect of the development in chronological order. There are a total of four key sections in this

report:

Technology review (2) This section will cover the different technologies that could be potentially used throughout the development and outlines the advantages and disadvantages of each one. This will lay the foundation for the design section.

Design (3) Focuses on the concept of the project, the design of the requirements obtained during the requirements-gathering stage followed by the design of the application such as the tools going to be used and the user interface and internal engine architecture.

Implementation (4) Will take the proposed designs and consist of the development of the application as well as presenting the technical implementation details/decisions.

Conclusion (5) comes after the implementation and reflects on the project to ensure that the application has met the aims and objectives originally set out. Furthermore, it discusses the specific features that will need to be implemented going forward in.

2 Technology Review

Prior to commencing work, a technological review must be undertaken that analyses and compares different types of potential tools that could be used. Throughout this comparison, the choice of potential tools is heavily influenced by the aims and objectives outlined in sections 1.3.1 and 1.3.2 respectively.

2.1 Version Control

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. Furthermore, 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.

2.1.1 Git vs SVN

Git 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](#).

Similarly, Apache Subversion (SVN) is another type of version control system.

Git	SVN
Some values	Some values

2.2 Development Environment

The project will be developed using a dedicated development environment which is a set of tools that provide helpful features. These features can include debugging, formatting, source code analyses, profiling and much more.

Microsoft Visual Studio 2022 This application is a fully-fledged Integrated Development Environment (IDE) that contains many different features that are dedicated to development. In addition to the application, it comes with the Microsoft Visual Compiler (MSVC) compiler which is Microsoft's own C/C++ compiler. The IDE together with MSVC create a solid ecosystem for development.

However, the main downside to this option is that it is only supported on the Windows operating system. Therefore, it's not available on macOS or Linux.

Microsoft Visual Studio Code Is a light text editor that is very flexible and has support for many extensions for debugging and other ide-like features.

JetBrains Clion Developed by JetBrains it is a C/C++ IDE for use with the CMake build system.

One of the major downsides to this application is performance. CLion was built using the Java programming language which runs on JVM (Java Virtual Machine). Parsing complex source code requires significant performance and if the IDE starts to slow down then this makes the developer experience must worse.

2.3 Programming Language

As a desktop application, there are several options for which programming language should be chosen with each one having its advantages and disadvantages.

Due to the nature of the application and its performance requirements, the language must allow VMVE to be compiled as a binary file. Furthermore, direct memory access and manipulation are required. There are three main candidates.

C Developed in 1972, it is one of the older programming languages and closest to the hardware. The language is quite rudimentary.

C++ This language is built on top of C and introduces a wide range of features such as classes, inheritance, type safety and the standard template library.

Rust Is the newest language and has been developed from the ground up with memory safety in mind.

2.4 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 7.3 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 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
	✓	✗	✗
	✓	✓	✓
	✗	✗	✗
	✗	✓	✓

Figure 2: Rendering API comparison

The image shows that DirectX APIs is not cross-platform and is only created to target Microsoft-backed operating systems such as Windows and Xbox. On the other hand,

2.5 External Libraries**2.6 Task Management**

Task management refers to the use of tools to aid in managing tasks or issues. Various tools are designed for this purpose however, there are two that are the most well-known which are Trello and GitHub Projects.

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.

3 Design

The design of the project consists of selecting the specific tools which will be used throughout the development as well as the design of the software and overall architecture.

3.1 Tools

3.1.1 GitHub

The version control system that was chosen for use throughout the development of the project was Git/GitHub^[6]. It's the most popular version control system and is the platform that I am most familiar with therefore, GitHub will be the platform of choice for this project. Appendix section [7.2](#) includes additional information such as how the repository is hosted.

3.1.2 GitHub Projects

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 [3](#) shows a preview of the Kanban board. It consists of three main columns used to categorise an issue including backlog, in progress and done.

When an idea for a new feature is formed or a bug within the application is discovered a GitHub issue is created and moved to the “Backlog” board. This is used to document a particular task that needs to be worked on within a desired timeframe.

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

Lastly, once the task has been completed, the GitHub commit that includes the specific fix is referenced in the issue and is then finally marked as complete by being moved to the “Done” board. This subsequently marks a GitHub issue as closed.

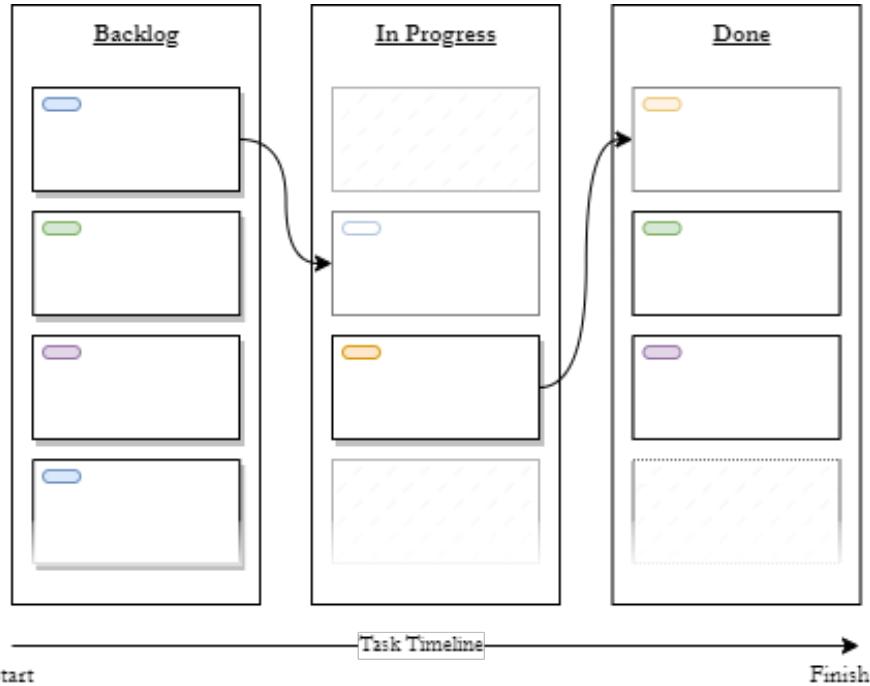


Figure 3: Kanban design

3.1.3 Microsoft Visual Studio 2022

- Chose VS 22 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 CPU will be able to understand and therefore, execute. MSVC also known as CL will be the compiler of choice. This is a compiler that comes bundled with the Microsoft Visual Studio IDE.

The IDE also provides debugging functionality that will be used extensively to fix crashes, and bugs and generally ensure 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 not provide such as reliable symbol renaming, file symbol outlining, quick

file searching and much more.

3.1.4 RenderDoc

As well as using software for debugging on the CPU, there also exists software that allows for debugging the GPU. More specifically, these tools allow for analysing per-frame data as well as detailed frame synchronisation metrics.

RenderDoc developed by Baldur Karlsson can be used to inspect different rendering 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.

3.1.5 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 analyses per-frame data which subsequently provides insightful performance metrics.

3.1.6 C++ 23

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.

3.1.7 Vulkan

Having evaluated the potential use of the different APIs covered in section 2.4, it was concluded that Vulkan would be the most suitable rendering API 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 work with the GPU. Furthermore, Figure 2 shows that the API provides most amount functionality including the ability to run on different operating systems, finer rendering control and support for multi-threading.



Figure 4: Vulkan logo^[11]

3.2 Libraries

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

3.2.1 ImGui

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^[12]. This is an immediate-mode user interface library that provides an API to render UI elements.

3.2.2 Crypto++

VMVE will include its own model file format. This is a custom 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++^[13] and the application will use version 8.7. This is a C++ library that provides many algorithms including AES, Diffie-Hellman, GCM, RSA and much more.

3.2.3 Cereal

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 serialise the data when saving to disk as well as deserialise when loading a “.vmve” model. To achieve this, the cereal C++ library will be used^[14]. This library allows for fast and efficient data serialisation into different formats such as compact binary encodings, XML or JSON.

3.2.4 Summary

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

3.3 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 recognisable results in an increase in brand recognition that may also increase user traffic.

3.3.1 Project Name

VMVE stands for “Vulkan Model Viewer and Exporter”. The name is made up of two parts. 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 3.2.2. The combination of these two allows a user to have a basic understanding of what the application does without having used it before.

3.3.2 Logo

There are two versions of the VMVE logo that was designed and intended to be used in different scenarios. The first is the complete logo as seen below in figure 5 which is referred to as the “large logo”. It contains the icon and the name of the application to the right of that.



Figure 5: VMVE Large Logo

This is to be used on the VMVE website as well as documentation pages providing consistent branding across different mediums.

The second version is designed to be minimal and therefore, only consists of the icon. This is intended to be mainly used throughout the application and in locations where there is a minimal amount of space such as the Windows taskbar.

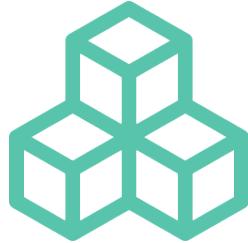


Figure 6: VMVE Small Logo

3.4 Project Architecture

3.4.1 Version Control

As the only developer for this final-year project, the design and architecture of the VCS will remain as simple as possible while still providing the core requirements. Figure 7 shows the proposed VCS architecture and includes two branches named “main” and “develop”. Develop branch will be the primary branch used throughout the implementation stages. In other words, when changes occur throughout the source code, all commits will be published to the development branch.

On the other hand, “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.

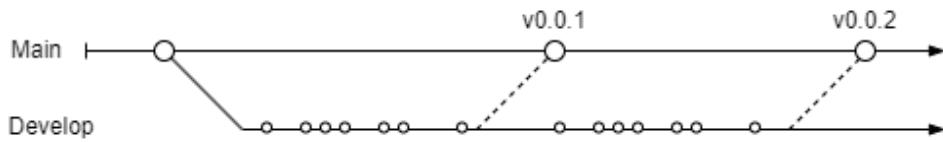


Figure 7: Git branch design

This architecture ensures that as the sole developer of the project, changes can be made consistently while ensuring that users are provided stable versions of the application.

3.4.2 Source Code

The source code for the application and overall architecture are to adhere to the C++ core guidelines^[15] to ensure that the project follows best practices. 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 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^[16] 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 regarding source code style can be seen in figure 8.

```

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 }
```

Figure 8: Source code convention

VMVE will also be developed in a functional style and by using “structs” instead of an object-oriented one with “classes”. This is primarily related to the ease of use in terms of development since data can be more easily

accessed and manipulated. Furthermore, this will eliminate the need for getter and setter functions that needlessly take up source code space and is redundant when member variables are accessible.

3.4.3 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 Audio. 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 library (.lib file). A high-level overview of the project architecture can be seen in figure 9. Furthermore, by making this distinction between the core and VMVE, it will allow for the same sets of tools and technologies to be used in the future for other similar projects.

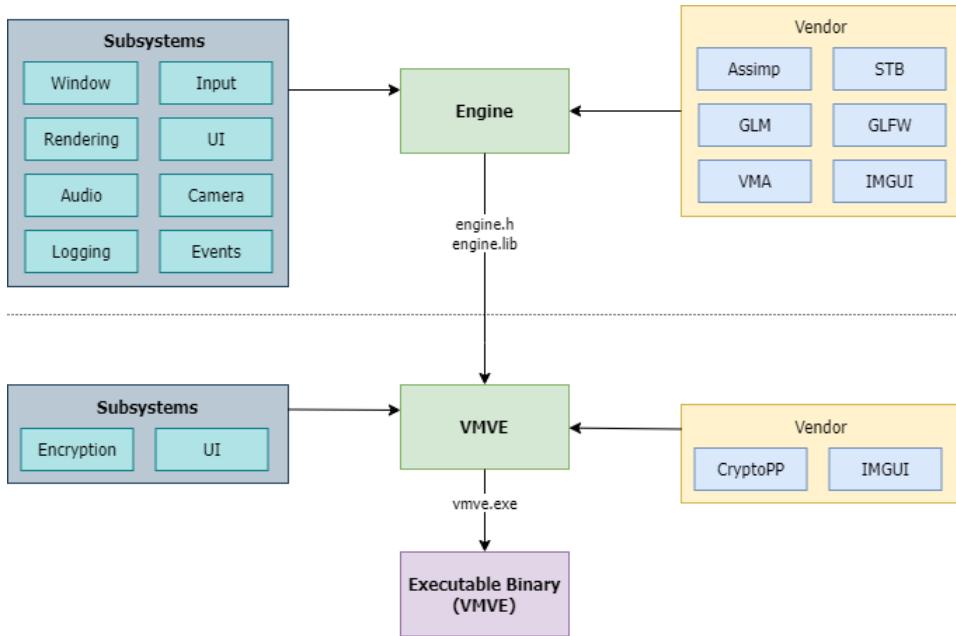


Figure 9: Project Architecture

3.4.4 Platform Architecture

The application will be developed to take advantage of the 64-bit platform. This would allow for the application to go beyond the 4GB limit posed by 32bit programs. In addition to this, 64-bit provides better performance and security as a result of the larger address space.

3.4.5 Renderer Architecture

As mentioned in section 3.1.7. 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 Vulkans verbose API.

Therefore, the renderer must be designed so that flexibility is maintained whilst simplifying the [API](#). Figure 10 shows the proposed renderer architecture which makes distinctive boundaries and encapsulates key sub-systems.

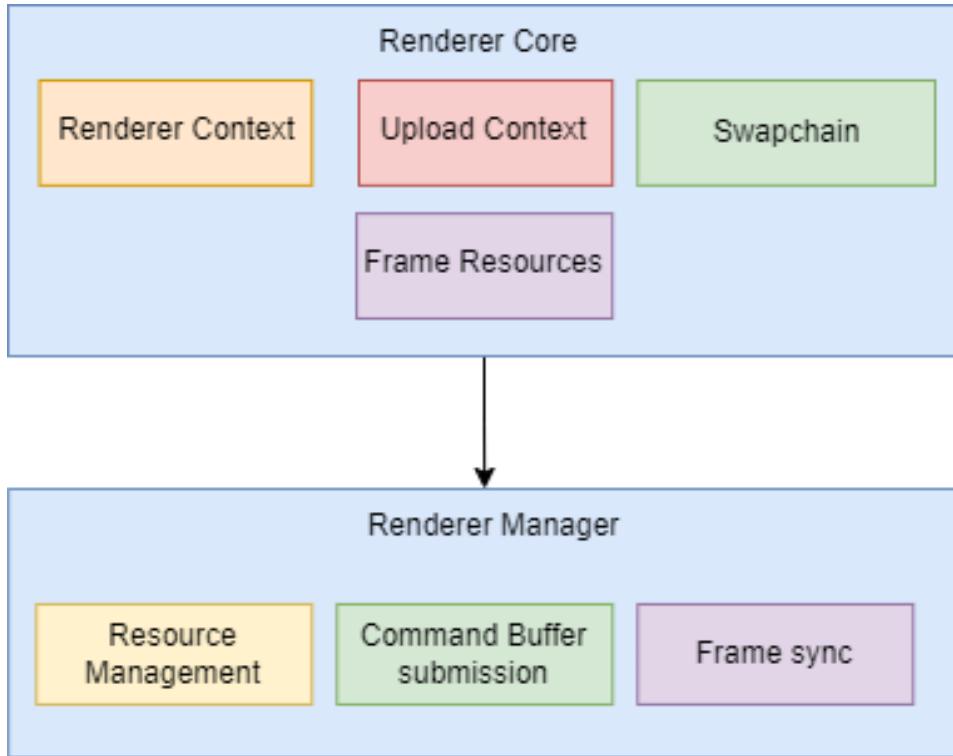


Figure 10: Renderer Architecture

3.5 User Interface

Designing the user interface was the next step as part of the design stage of the project. Figure 11 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.

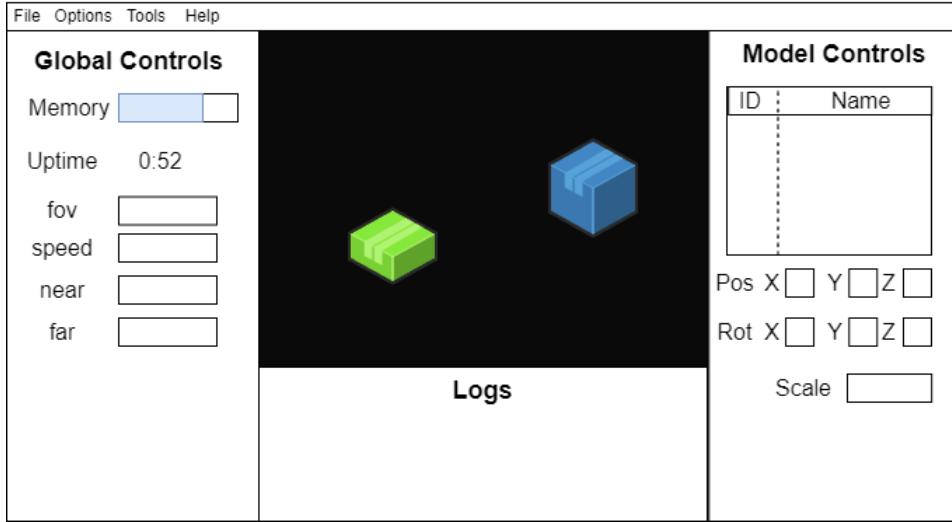


Figure 11: UI Design

The purpose of the user interface is to provide an easy-to-use platform for interacting with VMVE and more specifically the main viewport located in the center of the application.

3.5.1 Main Viewport

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

3.5.2 Global Panel

Located on the left side of the application, the global controls panel will contain user interface elements that apply globally such as general application information and camera controls.

3.5.3 Model/Entity Panel

The right side panel called model controls will display model and entity specific information and will be the primary control surface for interacting with objects in the virtual environment.

3.5.4 Logs Panel

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 categorised 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.

3.6 Custom File Format and Encryption

3.6.1 File format

VMVE will include a custom file format that allows for model data to be encrypted for security purposes. Figure 12 shows the proposed internal structure of the file. The internal structure is split into two main sections. The header contains key pieces of information that help the application determine how and if the main data should be decrypted.

Version indicates which version of VMVE was used to encrypt the file.

At the moment, this is to be purely informational however, in future versions, this can be used for reporting compatibility issues and also, allowing for encrypted files to be updated to newer file layouts.

Mode is the encryption algorithm used (e.g AES, DH) and is what will allow the application to know which decryption algorithm needs to be used.

Encrypted Keys is used for validating the input key and initialisation vector. If these match then the application will then decrypt and load the data.

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

The remaining section of the file consists of the encrypted data which includes the raw model data.



Figure 12: VMVE File internal structure

3.6.2 Encryption and Decryption

When dealing with encryption there are two primary stages, encrypting and decrypting. The term “encryption” means taking some data and running it through an algorithm making the data unreadable. “Decryption” is the opposite of that which takes the unreadable data and turns it back to the original data.

Designing such a system requires careful consideration and extra care to ensure that the data being managed is not negatively affected such as information being lost when converting from one stage to another.

The primary encryption algorithm that will be used is AES and the key length can be two different values (128 or 256 bits) that the user will choose based on the level of security they want for their assets.

Figure 13 shows a flowchart describing the general process of how a model will be loaded into VMVE.

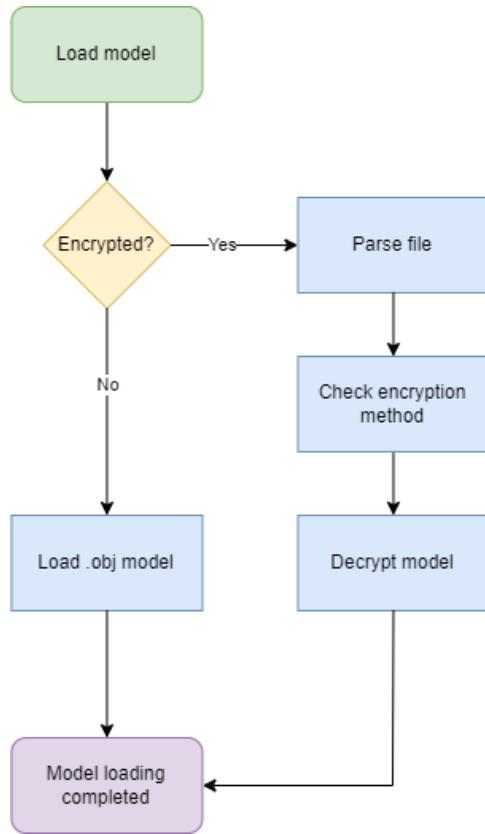


Figure 13: Load model flowchart

Likewise encrypting a model will consist of three main stages which are loading, encrypting and exporting as show in figure 14.

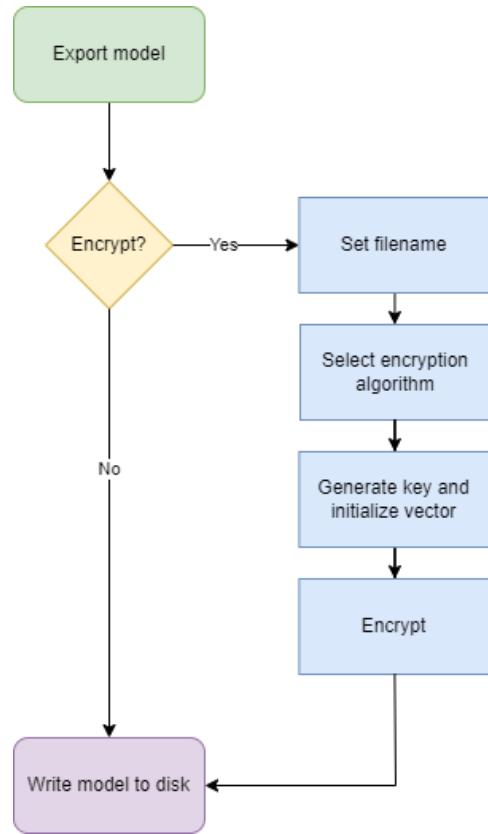


Figure 14: Export model flowchart

4 Implementation

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

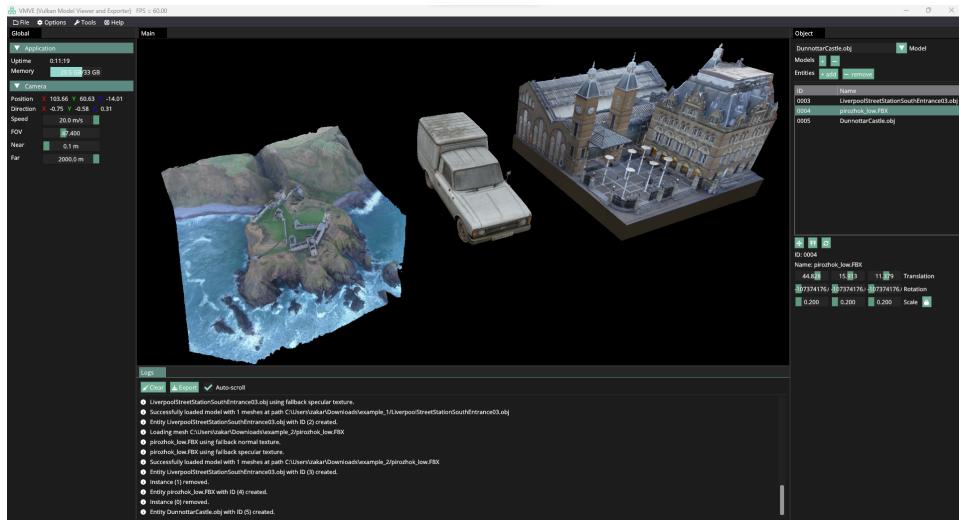


Figure 15: UI implementation

4.1 Overview

Figure 16 shows the general overview of the application and the various stages that occur during initialisation, runtime and shutting down. The application is a complex system that consists of various subsystems that work together.

```

1
2 int main()
3 {
4     // begin application initialisation
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 16: Implementation overview pseudo code

4.2 Window System

The first system within VMVE that gets initialised 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.

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.

4.3.1 Renderer Context

The first step in creating the renderer is initialising an object called “vk_context”. This object is created within the application that groups Vulkan handles that are responsible for initialising 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 [10](#).

```

1 struct vk_context
2 {
3     VkInstance           // Initialises 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 initialisation of the renderer context can be broken down into several stages. The first of these states acquires 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*”^[17], 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

A swapchain is a series of images also known as framebuffers used by Vulkan that allocates a region of memory that stores frame data i.e pixel colors. As the name suggests, a “swapchain” is a chain of these images. The most common number of images is two or three which is called “double-buffering” and “triple-buffering” respectively. The renderer within VMVE is configured to use two images, one for the front buffer that is shown on a monitor and a back buffer that is used for rendering.

In addition to buffers, a swapchain is also responsible for handling vertical refresh rate also known as vsync. This is the rate at which new images are rendered and then presented on a user’s screen. There are two main types of vsync modes used within Vulkan which are `VK_PRESENT_MODE_FIFO_KHR` and `VK_PRESENT_MODE_IMMEDIATE_KHR`. The “fifo” mode indicates to the swapchain and subsequently, the presentation engine that images are to wait for the monitor’s refresh rate before being present whereas “immediate” simply renders images as fast as possible.

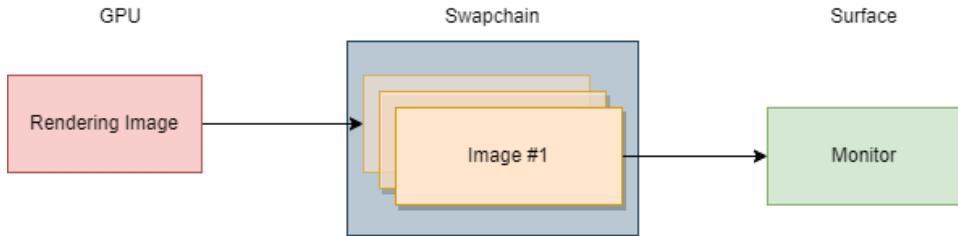


Figure 17: Swapchain

VMVE uses the “fifo” presentation mode as it conserves hardware resources as new images will not be rendered needlessly. Also, this mode ensures that no screen tearing occurs between refresh rates. Figure 19 shows a detailed image regarding the presentation engine and frame synchronisation.

4.3.3 Frame synchronisation

Once the swapchain along with its framebuffers has been fully initialised, the renderer can now start creating the necessary resources required for frame synchronisation. Vulkan has two concepts that relate to synchronisation 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 18: Frame sync structure

The Vulkan 1.3.246 specification states that “`VkFence` is a synchronisation 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 synchronisation 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.

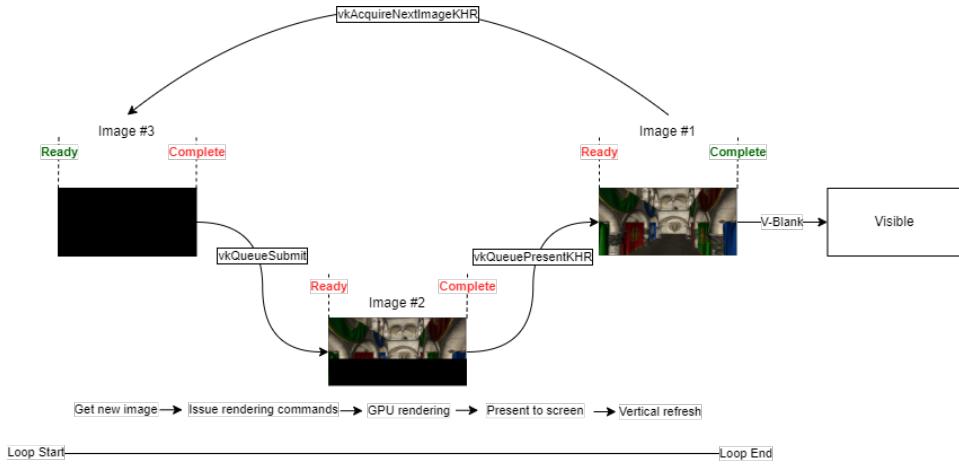


Figure 19: Frame Synchronisation

4.3.4 Deferred Rendering Pipeline

The next rendering feature that was implemented was a deferred rendering pipeline. During rendering, there are two main passes. The first pass renders the raw geometry data and performs MVP translation (section 4.3.9). For each rendered frame a total of five framebuffers are filled with different types of information including colors, world positions, normals, depth and specular.

Then the second pass reads the data from the five framebuffers and performs the lighting calculations. This is a common technique in rendering applications that significantly improve performance when large numbers of light sources are present compared to forward rendering. This is because deferred rendering defers all lighting calculations to the final pass and only needs to perform those calculations once. However, for forward rendering, this needs to occur for each object in the scene resulting in poorer performance.

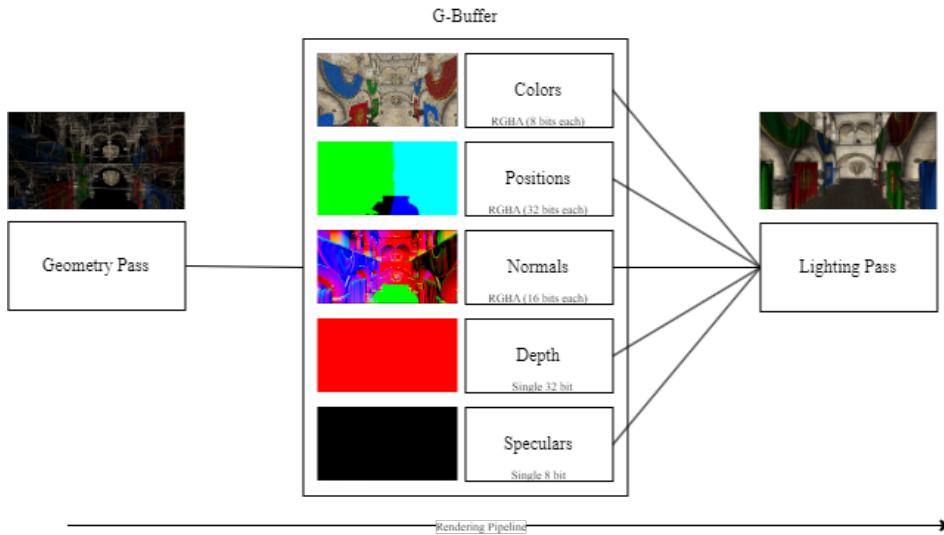


Figure 20: G-Buffer Pipeline

4.3.5 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. Figure 21 shows the internal structure of a dynamic uniform buffer that stores three sub-regions of memory in a triple-buffered frame setup.

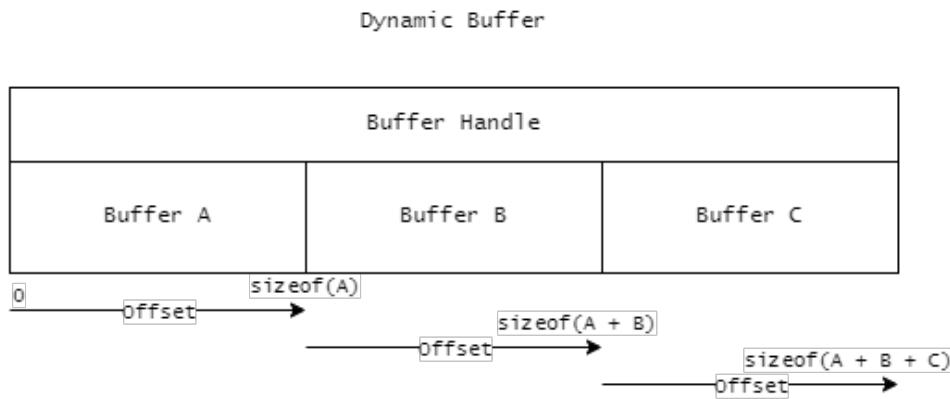


Figure 21: Dynamic Uniform Buffer

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

4.3.6 Texture Mipmapping

VMVE makes use of a rendering technique known as “Texture mipmapping”. This improves the visual fidelity by reducing if not eliminating Moire patterns which are visual artifacts that appear when identical patterns/textures are transformed on the screen [18].

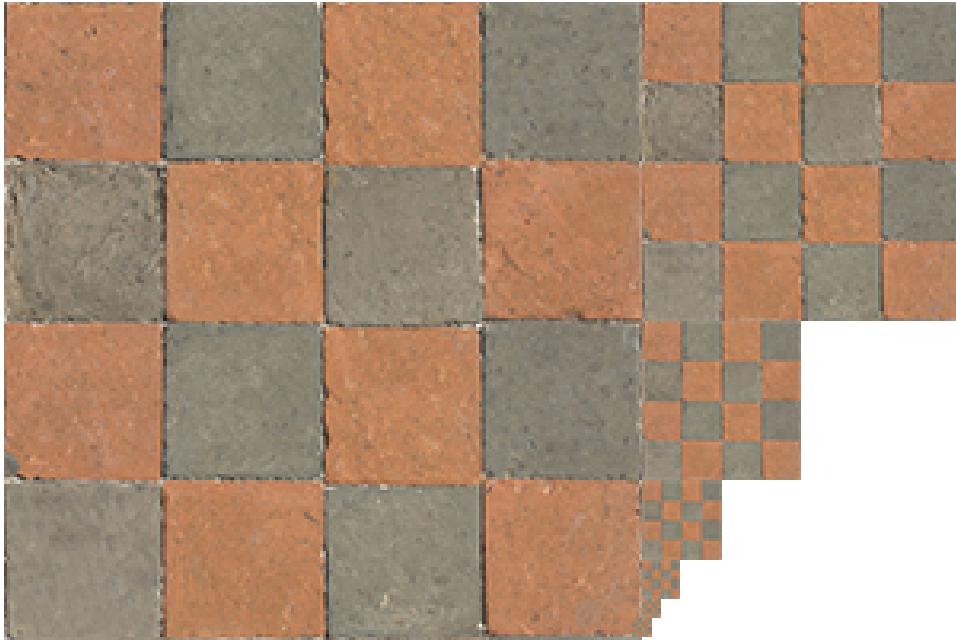


Figure 22: Texture mipmapping
[\[19\]](#)

Using Vulkan, this is implemented by taking the originally loaded texture and continuously halving it on both the width and height so that the subsequent texture is a quarter of the previous size. This is performed using the following equation provided by “Sascha Willems”.

$$m = \lfloor \log_2(\max(w, h)) \rfloor + 1 \quad (1)$$

where m is the number of mipmap levels, w and h are the width and height of the source texture respectively. For each texture mipmap created the size of the texture becomes exponentially smaller.

In the source code, it looks like this:

```
1  const auto mip_levels = static_cast<uint32_t>(std::floor(
2      std::log2(std::max(width, height)))) + 1;
```

Figure 23: Mipmapping equation

4.3.7 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. Each mesh has its own vertex and index buffers stored on GPU that describe to Vulkan how the piece of geometry is to be interpreted.

Figure 24 shows the internal structure of an example model which has been loaded into VMVE.

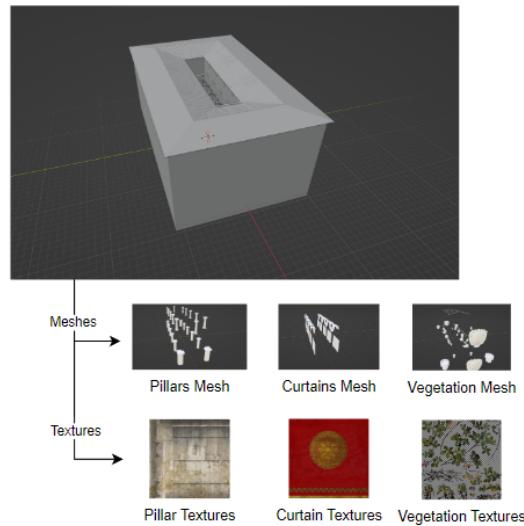


Figure 24: Model Structure

When a user loads a model, the model is appended to a continuous array (`std::vector<Model> models;`) which is iterated over each frame in order to render all the models on the screen.

4.3.8 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 25 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 4.3.9.



Figure 25: Multiple entities in virtual environment

4.3.9 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 them onto a 2D image for it to then be displayed on a monitor. This transformation is known as perspective projection [20] and is accomplished by computing several intermediate coordinate spaces as seen in figure 31.

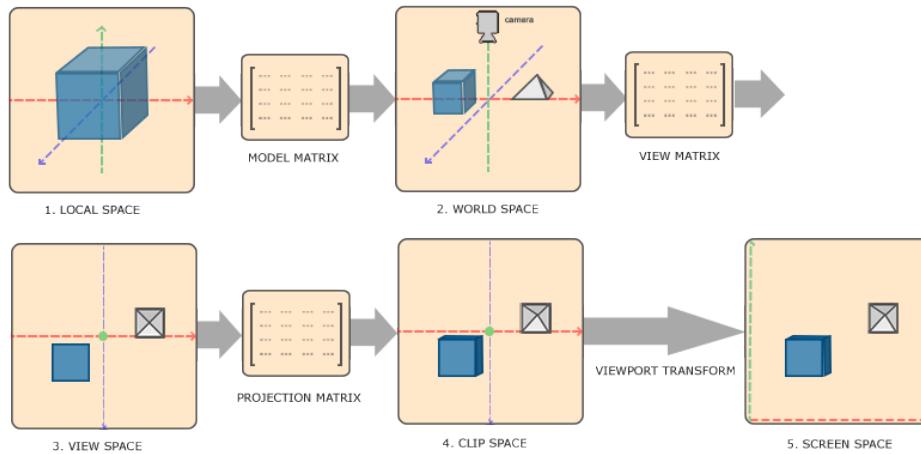


Figure 26: MVP Transformation [21]

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 27.

```

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 27: 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 visualisation of this is shown in figure 28 courtesy of a blog post by Jordan Santell <https://jsantell.com/model-view-projection/>.

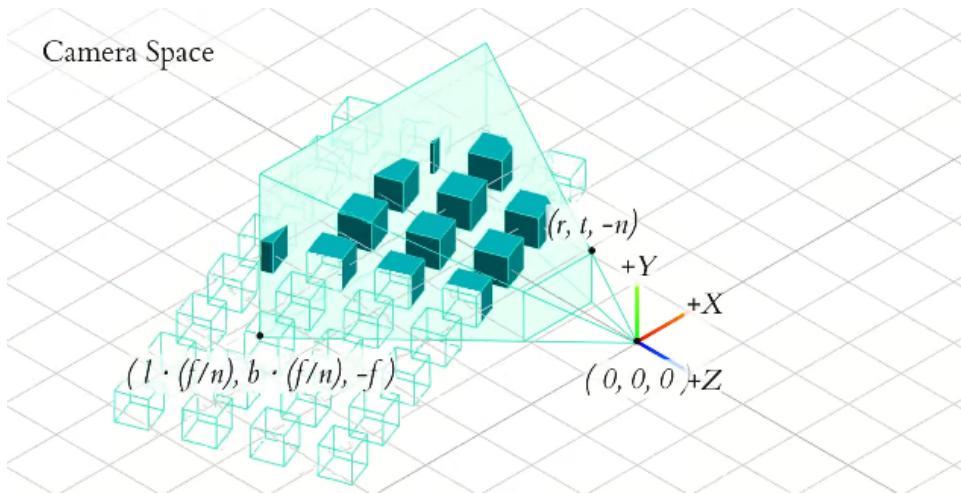


Figure 28: Camera/view projection [22]

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.

```

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

```

Figure 29: View matrix construction

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.

```

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

```

Figure 30: Projection matrix construction

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

$$Output = MVP \times Vertex \quad (2)$$

Figure 31: MVP projection

A more detailed code example can be seen in figure 69 in the appendix.

4.3.10 Lighting

The implementation of lighting was the final rendering system that was implemented. Lighting in Computer Graphics refers to how the virtual environment i.e. the colors of the resulting pixels are manipulated based on certain properties such as light, surface direction, occlusion, emissive materials and more. The use of lighting significantly improves the visual fidelity of the graphics and increases the realism.

The lighting model that was implemented is called Blinn-Phong which derives from the original Phong model was developed by Bui Tuong Phong in a paper titled “*Illumination for Computer Generated Pictures*” published in 1975 [23]. It describes three main elements including ambient, diffuse and specular lighting that works together to produce the final result.

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

$$A = G + P \quad (3)$$

Diffuse 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 of an object based on the angle off a particular surface.

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 equal to or less than 0 then it indicates that the light is behind the surface and thus, is clamped as a result of the max function which returns the largest value for the given two parameters.

$$I = \max(\vec{L} \cdot \vec{N}, 0) \quad (4)$$

$$(5)$$

Having calculated the intensity value we can now simply multiply it with the objects' surface color as shown in the equation below.

$$D = I \times C \quad (6)$$

Figure 32 demonstrates a simple example of diffuse lighting and how light interacts with an object based on the various properties discussed.

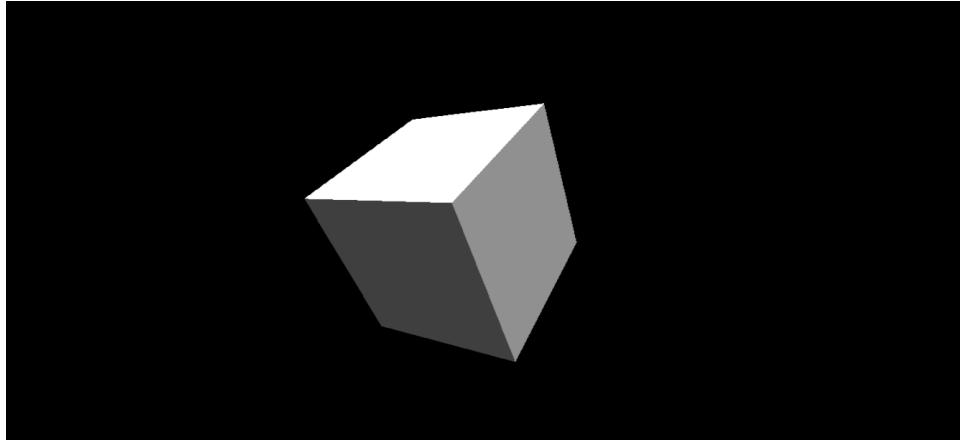


Figure 32: Diffuse Lighting

Specular The final step in the Blinn-Phong lighting model is specular. This effect adds highlights to certain parts of an object and is where the intensity of light is strongest.

4.4 User Interface

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

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. Various built-in controls aim to increase 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^[24].

Typically, data for fonts and icons are stored in a font file which ends 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. A small example of what this looks like can be seen in figure 33. The full version of this is over 3000 lines long due to the vast 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,hLNDnx4Uu/>8Q7oo^eFb3hB4JYc'
Tx-31_wgd2Tf._r+&sAqV,-G"":F8LD=5,n]A&aA+<gXG-<iobW&>$>QJ8Z
.W$jg0Fv-o^(^JJnf4T"
5

```

Figure 33: Base85 encoded font

4.4.3 Menu Bar

The menu bar is a panel located at the top of the application and provides global and commonly accessed tools and functionality. Each option within the menu bar contains various properties that allow a to toggle key settings.



Figure 34: Menu Bar

File Has the main buttons for importing and exporting models. It also provides convenient “Exit” button to free all resources and terminate the application.

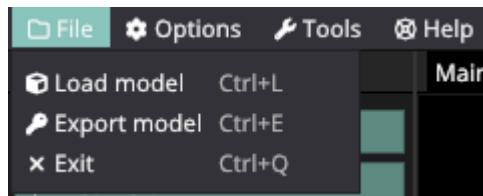


Figure 35: Menu Bar File

Options This is possibly the most frequently used item within the main menu as this has all the key options for the renderer and various visualisation tools.

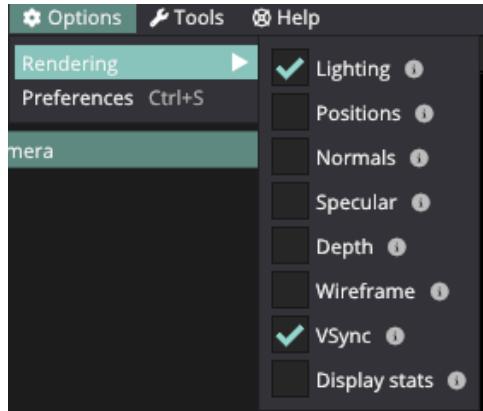


Figure 36: Menu Bar Options

Tools As well as rendering, VMVE will provide many other tools such as audio, a built-in console, an editor etc. To facilitate this, a dedicated tools menu is included. Currently, this acts as a prototype but in the near future will contain a plethora of fully featured supporting tools.

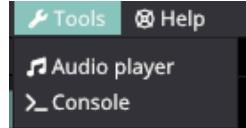


Figure 37: Menu Bar Tools

Help Lastly, the help option is for users who need additional assistance whilst using the application. It provides information about the application but also, a link that redirects users to the documentation website for VMVE

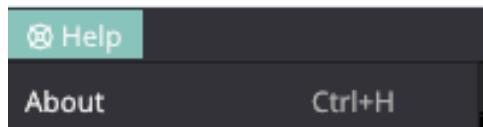


Figure 38: Menu Bar Help

4.4.4 Settings Window

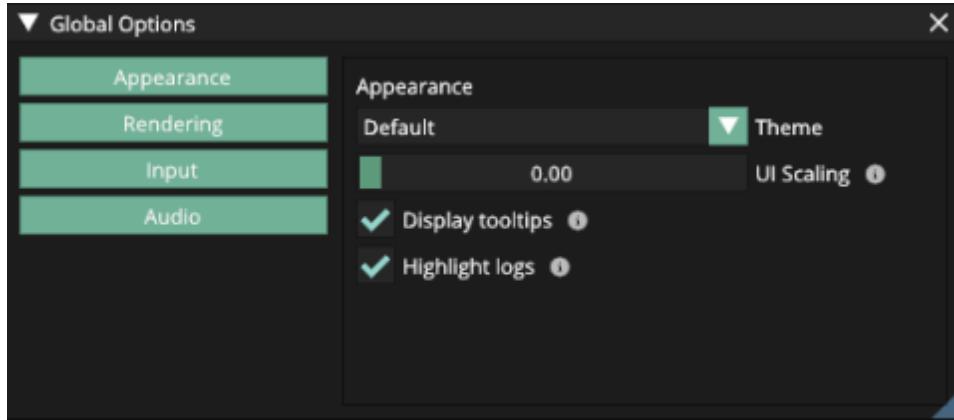


Figure 39: Settings Window

4.4.5 Load Model Window

The load model window is accessed through `File > Load Model` or by pressing the `ctrl + L` shortcut. The window displays the file system which contains a list of items and directories. The user can interact with this in order to load a 3D model at runtime.

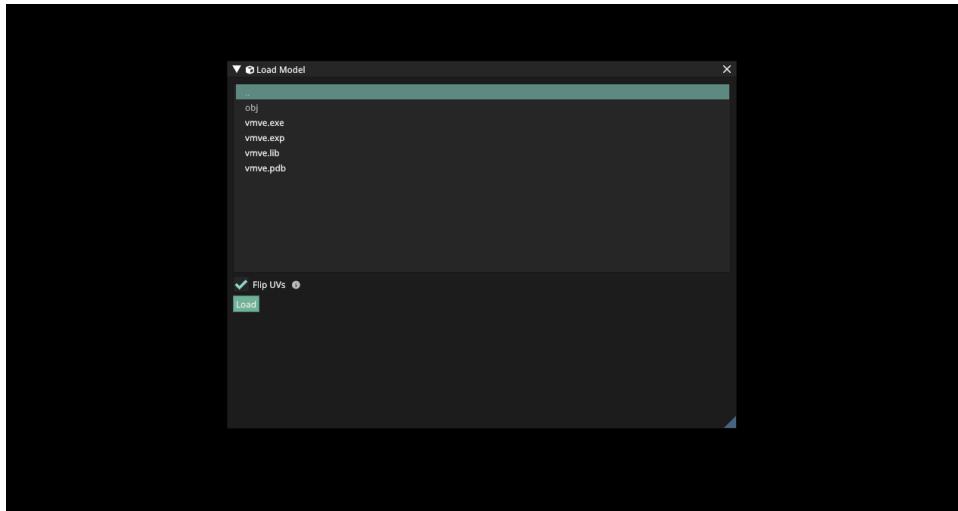


Figure 40: Load Model Window

If the 3D geometry file is detected to be encrypted then a modal window will popup asking the user to enter the files encryption key and initialisation vector.

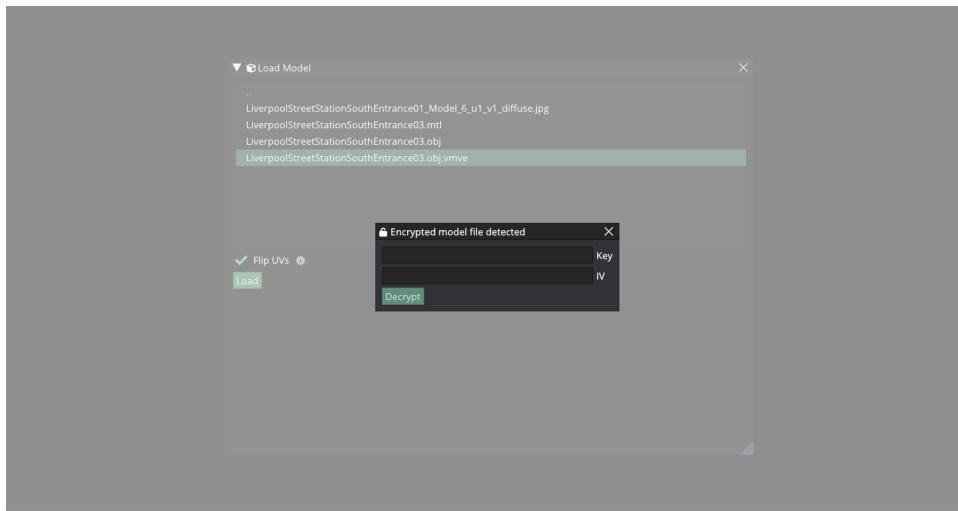


Figure 41: Load Model Encrypted Window

4.4.6 Export Model Window

The export window is responsible for encrypting and exporting models to the file system. There are two key options when encrypting a model which are the encryption mode and the length of the key. Users can change these options based on their security requirements. The next step is to generate the key and initialisation vector which can be performed by clicking on the “Generate key/iv” button. Finally, the model can be encrypted.

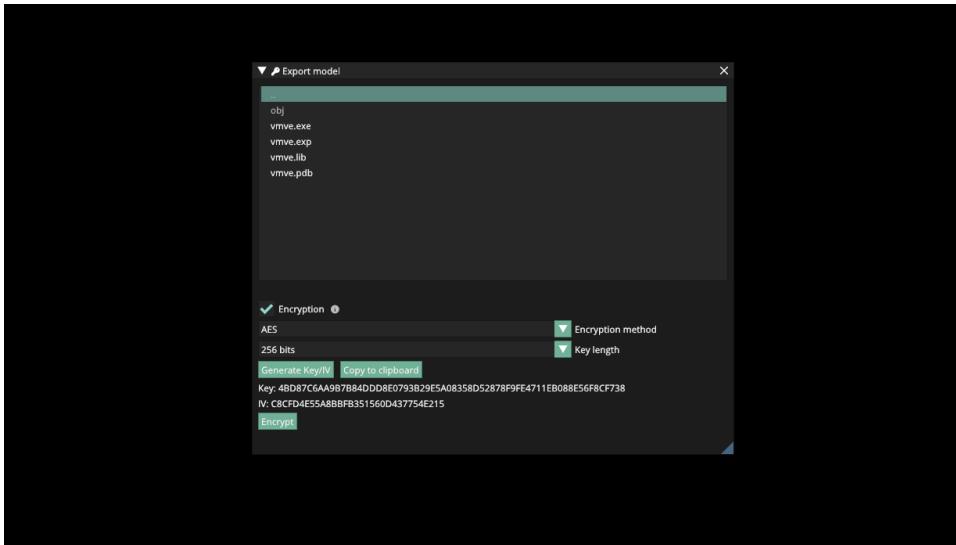


Figure 42: Export Model Window

4.4.7 Global Panel

The global panel contains application-wide information such as uptime and memory usage. Additionally, camera information and properties can be configured here which changes the way the virtual environment is rendered.

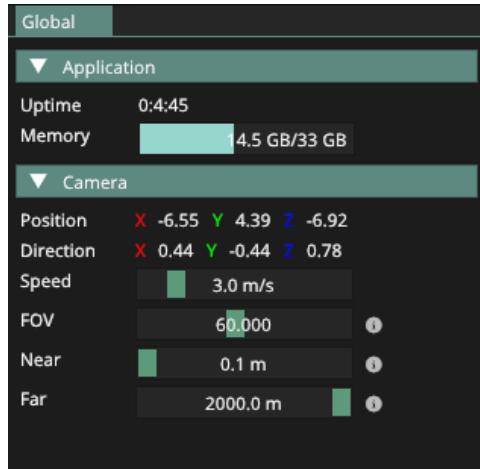


Figure 43: Global Panel

4.4.8 Entity Panel

The main method of interacting with entities in the virtual environment is through the entity panel. It contains a list of all loaded models in application as well as the entities as shown in figure 44. Below the entity list is dedicated controls for a specifically selected entity. This allows the user to manipulate the position, rotation and scale of an object in the world.

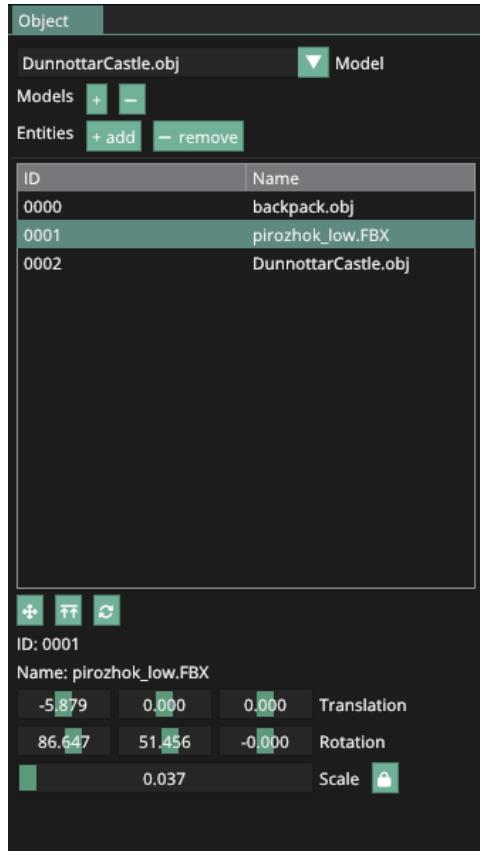


Figure 44: Entity Panel

4.4.9 Object gizmo

An additional feature that is part of the user interface is the gizmo. This is a visualisation of one of three operations 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 45 respectively.

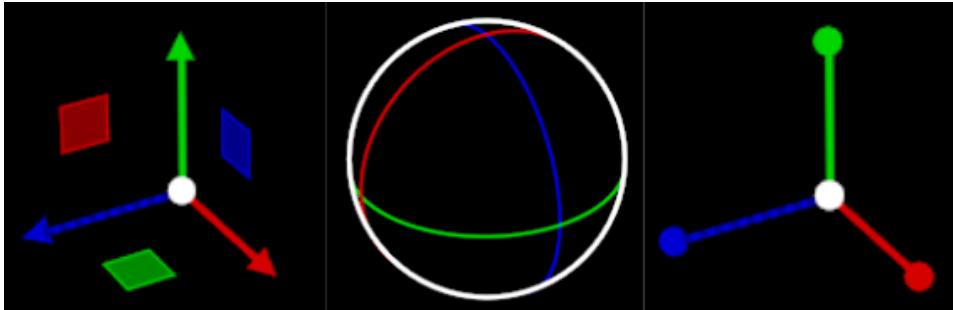


Figure 45: Gizmo operations

This functionality is implemented by taking the matrix transformation of an object and feeding that information to ImGuizmo^[25]. 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 user's screen. A small code snippet can be seen below 46 where M represents the model in the MVP projection.

```

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

```

Figure 46: ImGuizmo world to screen space

4.5 Logging System

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

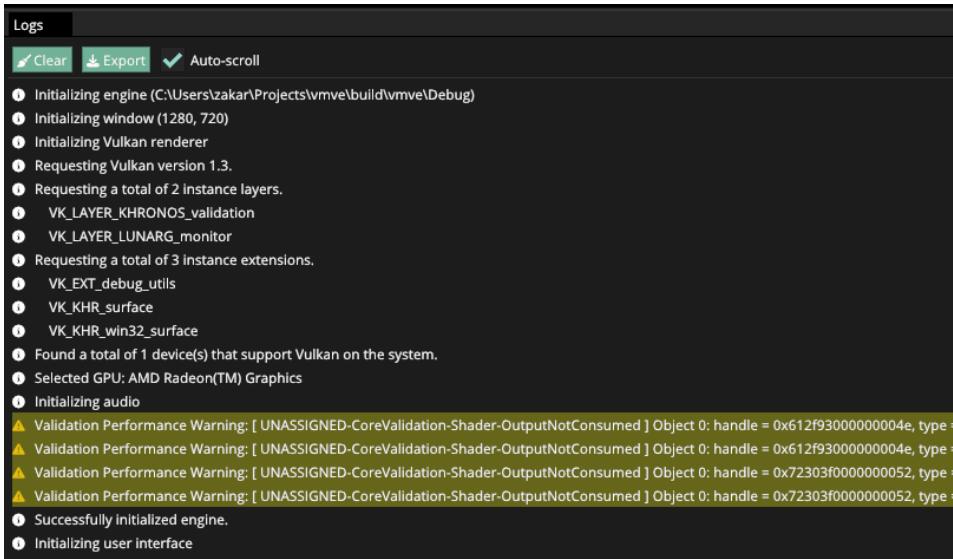


Figure 47: Logging window

Messages are stored in a data structure known as a ring buffer. This is a fixed-size buffer where the start and end of the buffer are connected. In other words, when the buffer becomes full, data stored at the start gets overwritten.

By default VMVE allows for a maximum of 200 log messages before the buffer becomes full. The underlying structure of this system can be seen in figure 48.

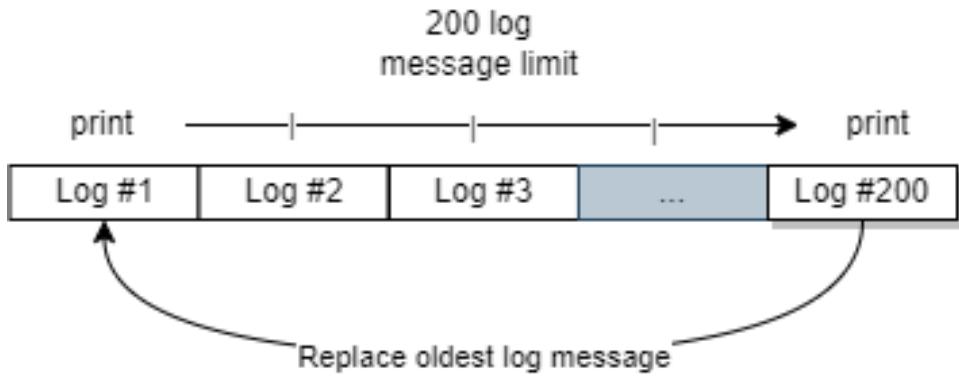


Figure 48: Logging FIFO system

The benefit of retaining log messages in memory as opposed to printing to the console is that they can be used at a later time such as for the UI or being saved to a file on disk.

4.6 Encryption and Custom Model Format

The simplicity of the Crypto++ library results in a relatively straightforward function, shown in Figure 49 which shows how a model is encrypted using the AES algorithm.

```

1     std::string encrypt_aes(const std::string& text,
2         encryption_keys& keys, int key_size)
3     {
4         std::string encrypted_text;
5
6         // Set key and IV to encryption mode
7         CryptoPP::CBC_Mode<CryptoPP::AES>::Encryption
8         encryption;
9         encryption.SetKeyWithIV(
10            reinterpret_cast<const CryptoPP::byte*>(keys.key.
11            data()),
12            key_size,
13            reinterpret_cast<const CryptoPP::byte*>(keys.iv.
14            data())
15        );
16
17        // Encrypt text
18        CryptoPP::StringSource s(text, true, new CryptoPP::
19        StreamTransformationFilter(encryption, new CryptoPP::
20        StringSink(encrypted_text)));
21
22        return encrypted_text;
23    }
24
25

```

Figure 49: AES Encryption

4.6.1 Decryption validation

When a model is being decrypted the system must check and ensure that the key and iv being used match those originally used to encrypt it. Without this check in place, the system will not know what the “correct” key and iv are.

As outlined during the design stage, the file header contains the encrypted key and iv. When the user enters their specific key and iv as input parameters into the decryption dialog box as shown in figure 41 in section 4.4.5, VMVE will first decrypt the header section and check if the input values match. If successful, the application will then proceed to decrypt the data section and then load the file. If however, this check fails, then the application will throw an error and prevent the file from begin decrypted.

4.7 Distribution

The distribution is an important final step during the development of the application which compiles and optimises the source code and makes the application available for end users. Before compiling, the project configuration is switched to “Release” mode as seen in figure 50.

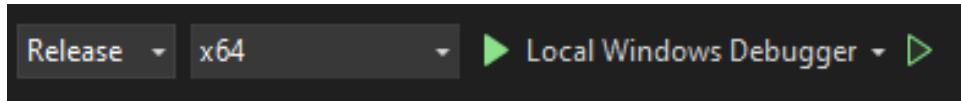


Figure 50: Project configuration

As mentioned in section 3.1.3, the compiler used is MSVC and therefore, specific compiler flags are used. One such flag is `02` which performs a series of optimisations during the compilation phase which maximises speed such as frame-pointer omission, inline function expansion, string deduplication, function-level linking and much more.

4.7.1 Executable

These optimisations ensure that the resulting application has a small executable size and performs efficiently. The resulting executable is named “`vmve.exe`”.



Figure 51: Executable

4.7.2 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.

4.7.3 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).

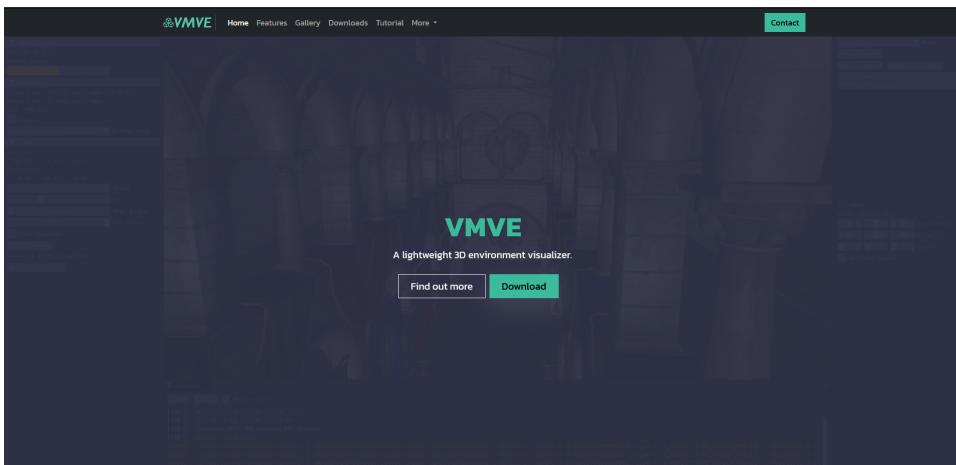


Figure 52: VMVE website

4.7.4 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.

example_1	23/04/2023 09:48	File folder
example_2	28/03/2023 00:30	File folder
example_3	27/03/2023 02:51	File folder
example_4	16/03/2023 01:56	File folder
example_5	16/03/2023 01:56	File folder
example_6	29/03/2023 17:23	File folder
credit.txt	28/03/2023 00:42	Text Document
		1 KB

Figure 53: Example models

4.7.5 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.

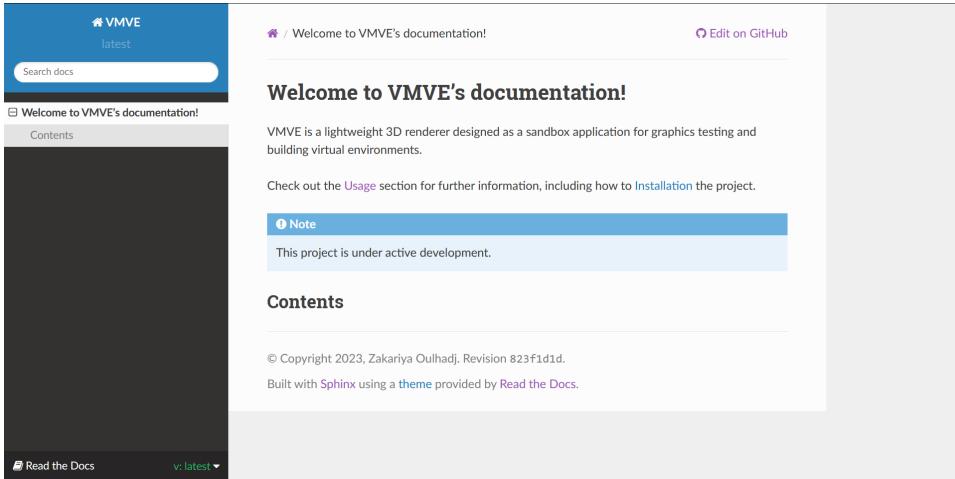


Figure 54: VMVE documentation

4.8 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.

4.8.1 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 initialisation stages. This would include creating the window, initialising the renderer, initialising 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.

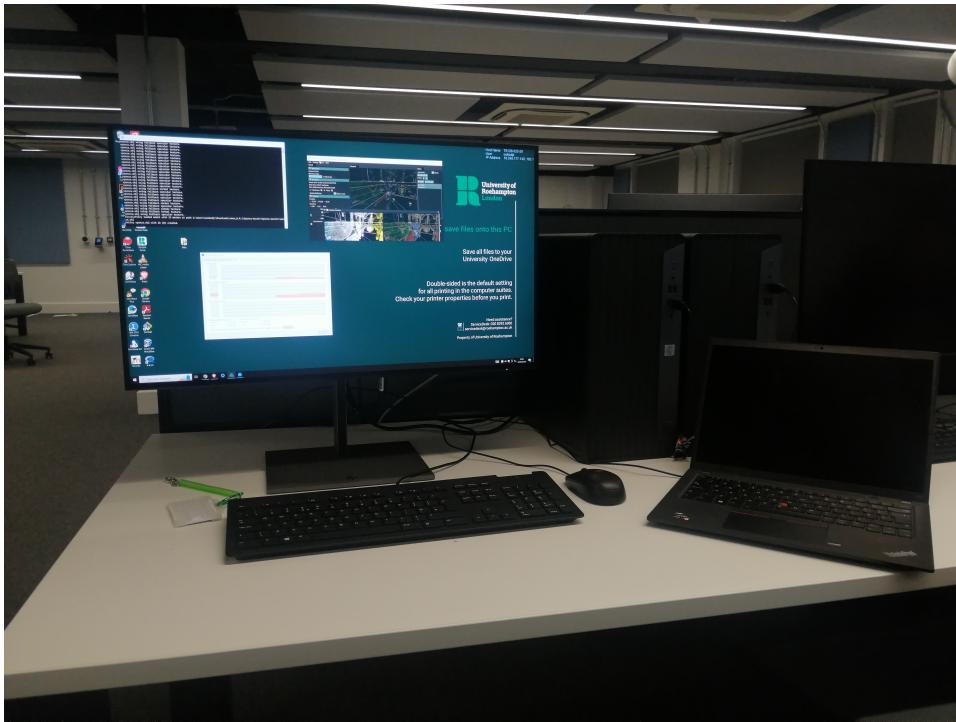


Figure 55: Working on distribution

During this part of development, the decision was made to design the logging system so that all messages in the buffer would be stored and written to disk before exiting. This allowed for unexpected crashes to be better understood as the `vmve_crash.txt` file could be analysed.

4.8.2 Time Management

Given the complexity of this project, it was vital to effectively manage time during development and to ensure that all of the 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.

As mentioned in section 3.1.1, GitHub was chosen and has been a highly effective tool throughout development regarding management and distributing tasks. Over 50 different GitHub issues have been resolved such as small user

interface issues, implementation bugs and major structural changes.

- 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

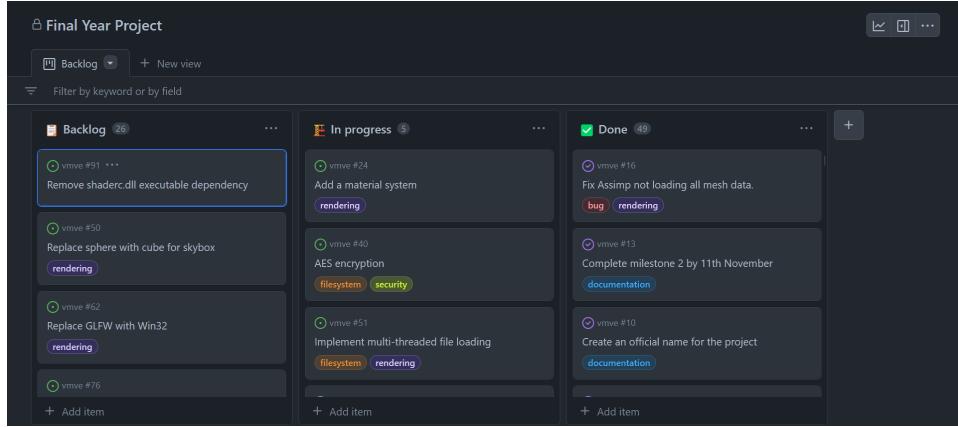


Figure 56: GitHub Issues Kanban

VMVE currently has 32 outstanding GitHub issues that have yet to be resolved. These issues are not considered critical and do not hinder the project in terms of meeting its original requirements. However, they are notable and should be resolved soon.

These tests were performed on the main development machine used throughout the project which was a Thinkpad T14s Gen 3. The following list shown in figure 1 shows the laptop's specifications.

Component	Name
CPU	AMD Ryzen 7 Pro 6850U
GPU	Integrated
RAM	32GB DDR6
SSD	1TB

Table 1: Development Machine

4.8.3 Performance

Measuring the performance of VMVE is another key aspect of evaluation that ensures the original goals and requirements have been met. Two main aspects can be measured which are 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 performance of the application while it is running and its effects on the end users.

A full clean build of VMVE takes an average of 53.260 seconds using Microsoft Visual Studio and the CL compiler. This includes the compilation of the source code and precompiled headers. 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 taken 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 intended to change often. This is because a change to any of the included header files will require a full precompiled header rebuild. 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.

This technique is done 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 header files and their corresponding source files.

CPU timing is primarily measured by calculating the difference in time at two specific sections of the source code. Using C++ this can be easily achieved by using the “chrono” library that allows for the duration to be calculated in different time units such as nanoseconds, milliseconds, seconds and more. The timing will be measured using milliseconds as that is the typical timescale for applications such as VMVE.

Using the aforementioned “chrono” library, the startup time for VMVE

averages around 300ms in the distribution version of the application which is calculated by taking away the time at the start of the initialisation from the end of the initialisation.

The Microsoft Visual Studio IDE allows us to further analyse this by taking advantage of the built-in profiler which can be accessed by going to **Debug** > **Performance Profiler**. Figure 57 shows the “flame graph” that takes a snapshot of the internal state of the application at runtime.

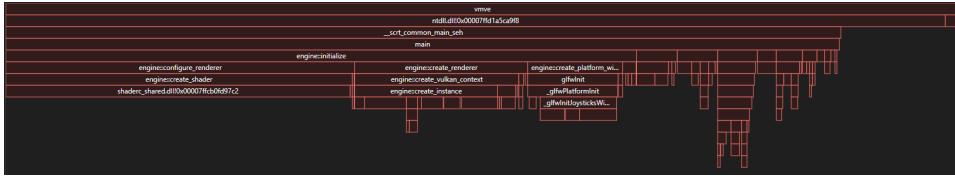


Figure 57: VMVE startup profiling

What this shows us is that a large chunk of the initialisation is taken up by the `engine::configure_renderer` function and more specifically the `engine ::create_shader` function which is responsible for compiling the application shaders.

This can be taken a step further by expanding the hot code path which is what Visual Studio refers to as slow code. Figure 58 shows the exact function that takes around 36% of the total initialisation time.

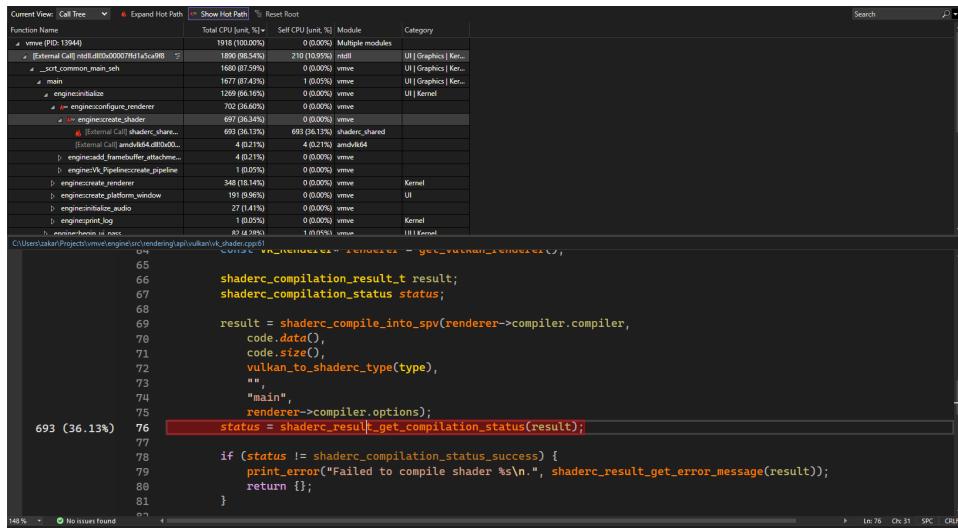


Figure 58: Profiling slow code path

The question one might ask is, “How can we improve this startup time?”. Currently, VMVE stores the shader source code as simple strings within a header file called `shader.h`. The main advantage of this is that shaders can be combined with the executable rather than be in separate files.

The downside to this, however, is that the shader source is not in a precompiled binary format, meaning that each time VMVE runs, it must recompile the shader files.

In the future, this will need to be addressed and the system redesigned in such a way that allows for shader files to be precompiled and bundled with the executable at the same time eliminating the need to compile shader files and as a result improving the startup time.

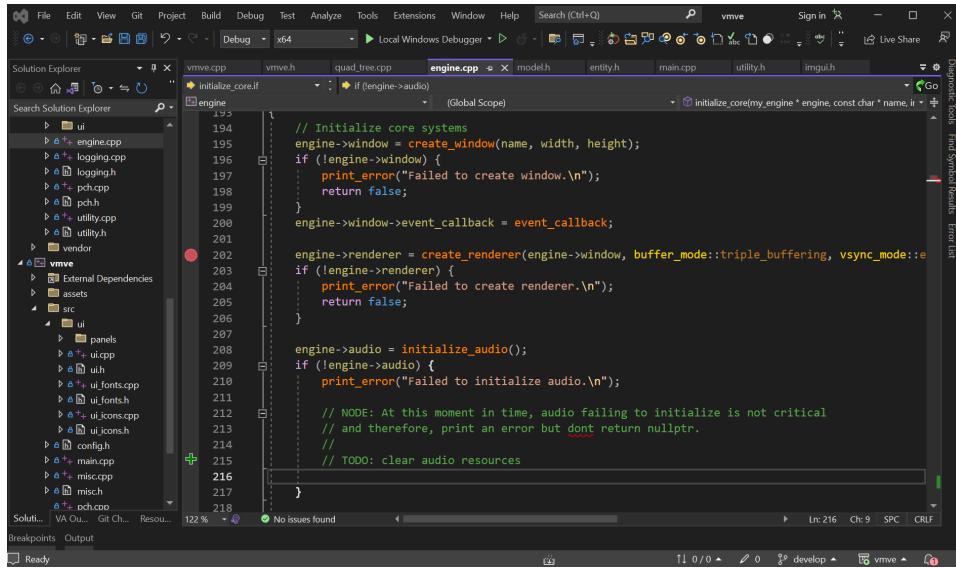


Figure 59: Microsoft Visual Studio

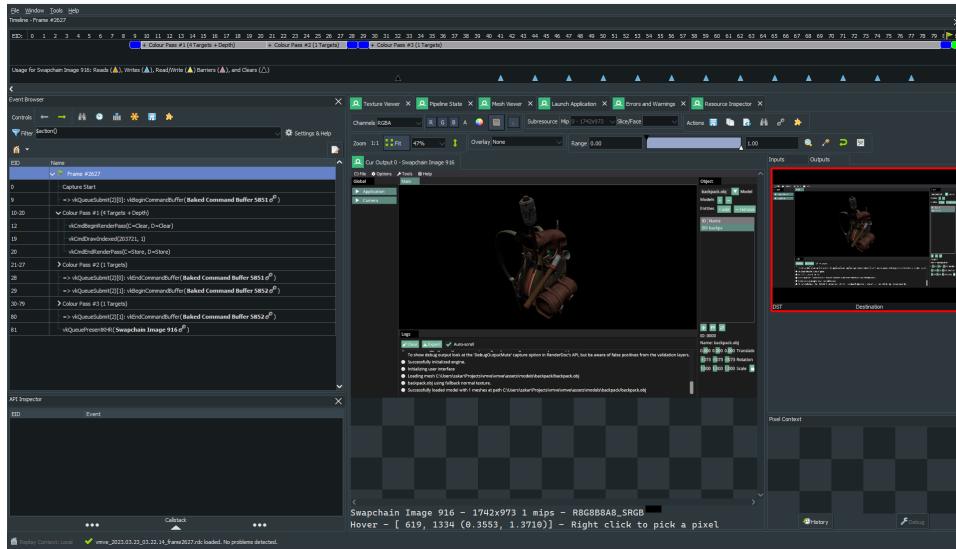


Figure 60: RenderDoc

4.8.4 User Feedback

Having conducted the evaluation, it is equally important to obtain feedback from the stakeholders such as 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 as seen in figure 61 [file](#). A score would be given for each task based on how easily the user was able to complete it.

Figure 61: User feedback instructions

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 using Google Forms and further analysed to produce different sets of visualisations.

The bar chart below shows the results of an ease-of-use test that was conducted between different users. The average ease of use score was 4.2. This indicates that the majority of the users found the user interface to be suitable for users regarding achieving their desired goals.

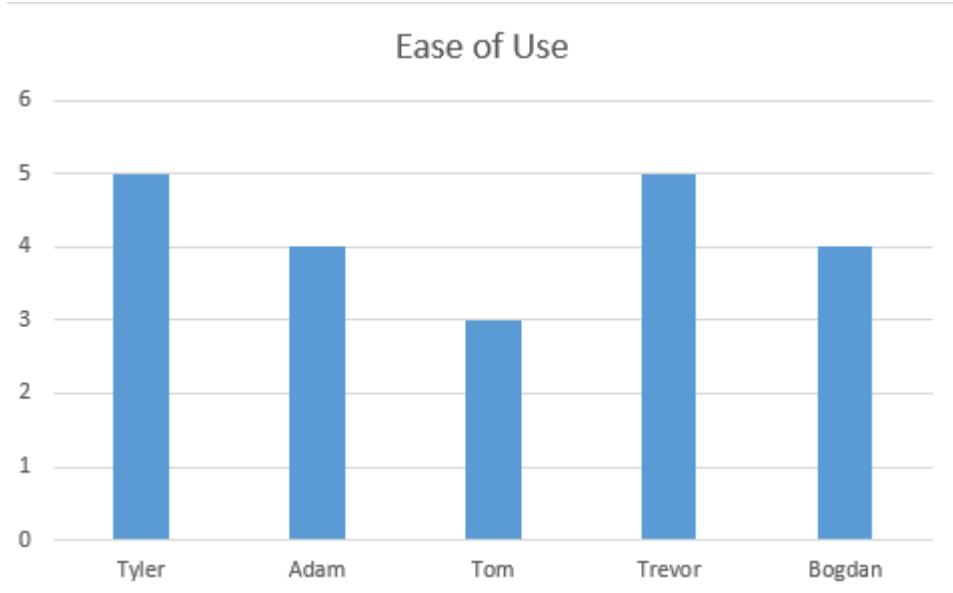


Figure 62: Usability bar chart

Tom who gave the VMVE an ease-of-use score of 3 said the following: “*Overall, the user interface is quite simple, however, I found that the shortcuts used throughout the application were not as easy to use as most required the use of two hands.*”.

This highlights an important issue in terms of ergonomics between the application and the user and as such will have to be addressed in the future.

4.9 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 - Use Google Scholar

5 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.

5.1 Reflection

This has been a long journey that has presented various challenges throughout the development of VMVE. Furthermore, a lot has been learned in different areas.

5.1.1 Time Management

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 serve as a basic prototype that showcases the underlying technology and the potential future work that can be undertaken.

5.1.2 Design

This project has also shown how important the requirements gathering and design stages are. For example, the rendering architecture took longer to implement as certain aspects were not fully realised and designed ahead of time.

However, it's also important to recognise that in large projects such as this, it can be difficult to fully define all the requirements as they may change over time. Therefore, this needs to be taken into consideration for design stages in future projects.

5.1.3 Alternative Rendering API

Vulkan which as previously discussed is a low-level GPU API. One of the major downsides to having chosen Vulkan as the API of choice for this project was the significant amount of time that 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, VMVE would be rewritten to use a simpler API such as DirectX11 or OpenGL as they provide the 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. In the future, if the renderer's performance becomes an issue then the use of more advanced APIs could be reconsidered.

5.1.4 Development Logs

At key stages of the project's 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>

5.2 Future Work

Looking forward to the future, several features need to be worked on and implemented that aim to greatly increase VMVEs usability and provide a whole host of new features that benefit the key stakeholder groups.

5.2.1 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, to support additional operating systems 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 for increased compatibility.

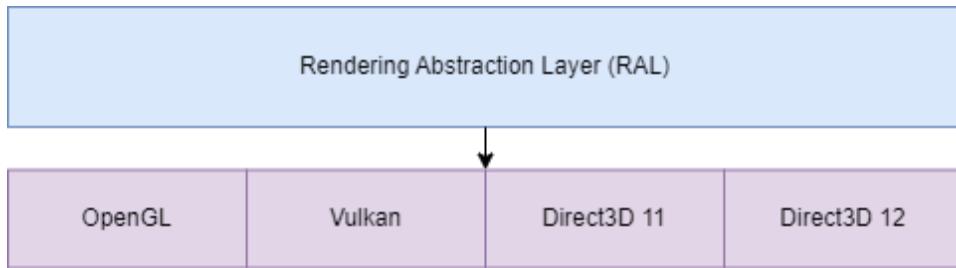


Figure 63: Rendering API Abstraction

5.2.2 Frustum Culling

Currently, VMVE sends all object data to the GPU to be processed and rendered. The GPU then subsequently traverses each vertex 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 optimisation 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 64 and “Culling” simply means discarding.

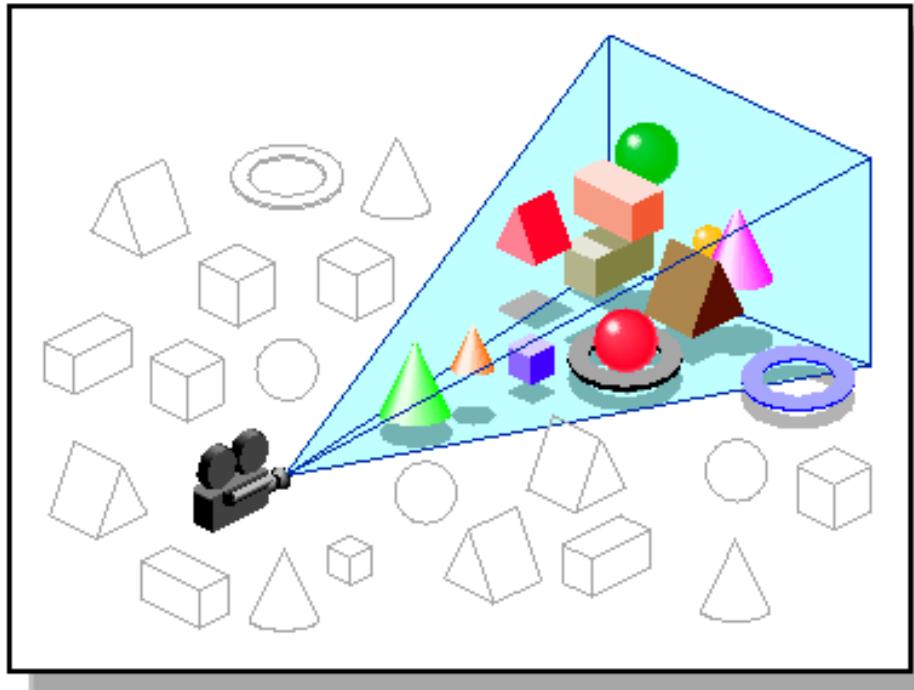


Figure 64: Frustum Culling^[26]

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 65. Then for each object, a check is performed against the bounded box instead of the actual vertices. This allows 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.

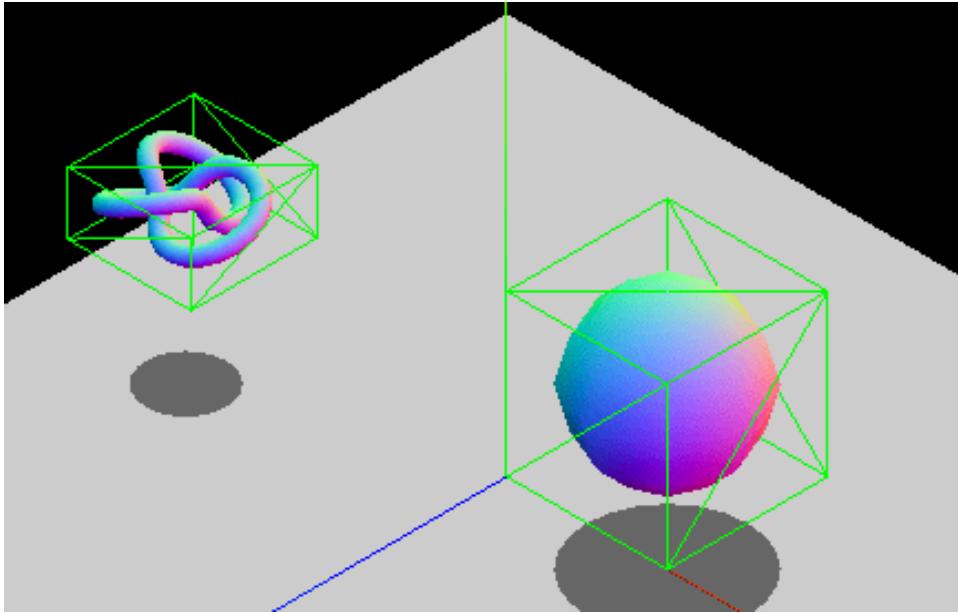


Figure 65: Bounding Boxes^[27]

5.2.3 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 66.

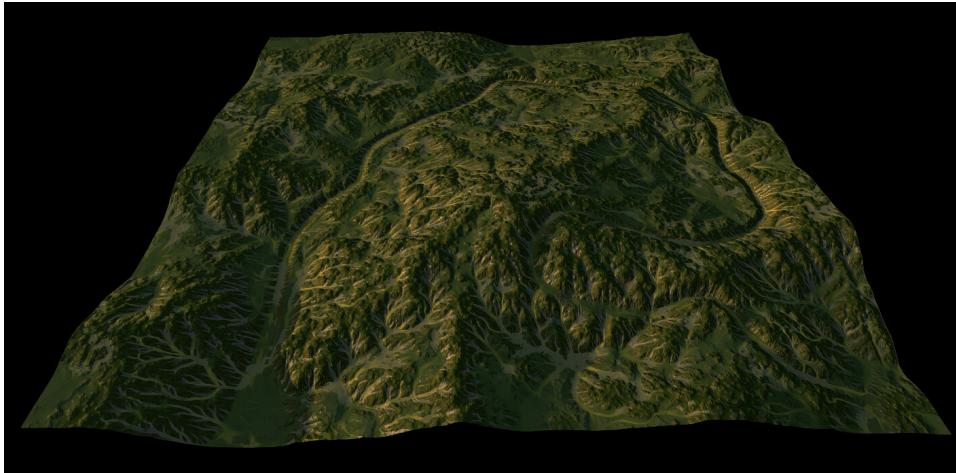


Figure 66: Large scale terrain

Currently, VMVE would struggle to render such objects due to their 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 of algorithms in the spatial domain including images and environments.

A quadtree is a type of spatial acceleration structure that stores a hierarchical collection of nodes that each represent a 2D area (and an octree in the case of 3D). Figure 67 visualises a quadtree that shows the resolution of each tile and how there are fewer tiles the further away from the camera they are.

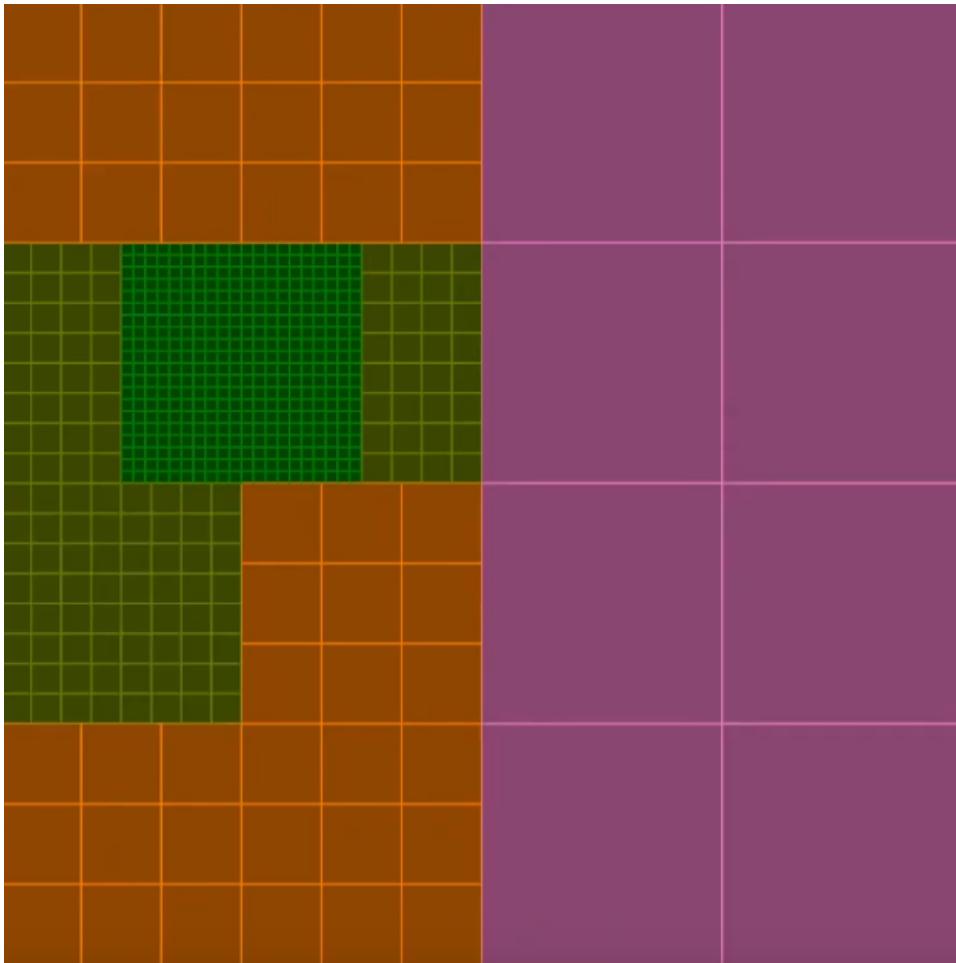


Figure 67: Quad Tree visualisation

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

5.2.4 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^[28] is a new model format by The Khronos Group that

has many useful features such as compression, binary representation, scene hierarchy and more.

5.2.5 Cross Platform

In contrast to the project's initial proposal which was the support multiple Operating Systems (OSs), Windows is the only OS that VMVE officially supports due to the time constraints for this project.

Going beyond the final deadline, VMVE should add cross-platform support which would greatly benefit the application as it would increase flexibility in terms of which OSs 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 different implementations depending on the OS being used. Additionally, a different build system would have to be used that is cross-platform such as CMake^[29] or Premake^[30].

5.2.6 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. For example, multiple users could work together to construct a virtual environment in preparation for scientific research which would otherwise have taken much longer had only one user worked on it.

5.2.7 File Format/Encryption

VMVE supports both the AES encryption standard by default. The application should also include additional encryption algorithms such as Diffie-Helm and RC6. This would provide users with greater flexibility in terms of how their assets are encrypted as well as varying levels of encryption strength/methods based on the user's encryption requirements.

Another feature that will need to be added to the application is related to the custom model format and the ability to store and encrypt other types of data. Currently, the encrypted data stores just the vertices and their

corresponding information. The downside to this is that assets such as textures are still required to be located alongside the “.vmve” file since the format does not support textures.

In the future, VMVE should be able to store textures so that users can be left with a single asset file that includes all the information, similar to how the glTF model format supports the “.glb” binary file. This would significantly increase the user’s experience since assets files would become easier to manage.

5.2.8 Runtime memory protection

One of the major flaws present is the lack of security that prevents a user from maliciously altering the memory of the application during runtime so that encrypted models can be accessed without the need for a valid key or iv.

This can be achieved using applications such as Cheat Engine which provides users with a set of tools for analysing memory addresses, offsets and values that can also be manipulated^[31].

This will need to be addressed in future versions of VMVE so that digital assets remain secure for all users.

5.2.9 Version Control

In regards to the VCS architecture, a potential change that can be done is to add a third branch called “Beta”. The purpose of this branch would be to release relatively stable yet unfinished features to users. This would allow users 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 on using recently developed features. Figure 68 shows how the VCS architecture could look like with the addition of a “Beta” branch.

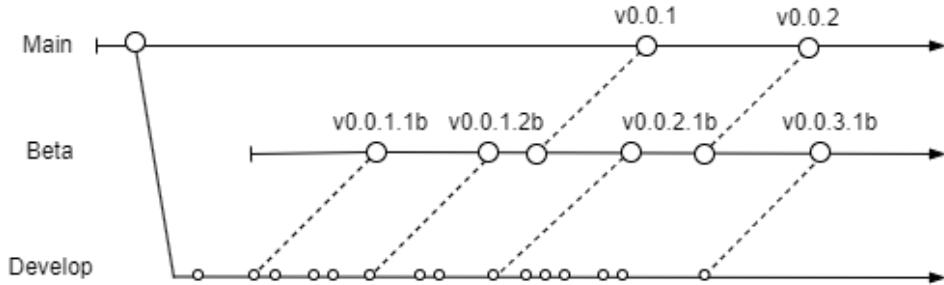


Figure 68: Potential future git branch design

5.2.10 Reduce Library Dependencies

VMVE makes use of several libraries which allows specific functionality to be added quickly. This is ideal given the project's 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 on external code, faster compilation times as only functionality that is required will be implemented and generally finer control of the code that VMVE is built on top of.

5.2.11 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 localisation. 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.

6 References

- [1] “Unreal engine,” <https://www.unrealengine.com/en-US/>.
- [2] “Unity,” <https://unity.com/>.
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7 Appendices

7.1 Supporting Documents

[Milestone 1](#) [Milestone 2](#) [Milestone 3](#) [Meetings Report](#) [source](#)

7.2 GitHub

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

7.3 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^[32] or NVIDIAs ADA^[33] 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, software drivers are 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 organisation 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 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.

7.4 Camera Transformation

```

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 69: Complete MVP example