VIETNAM NATIONAL UNIVERSITY OF HOCHIMINH CITY
THE INTERNATIONAL UNIVERSITY
SCHOOL OF COMPUTER SCIENCE AND ENGINEERING

A RESEARCH ON RECONSTRUCTION AND VISUALIZATION OF 3D OBJECTS ON VR APPLICATION

By
Đinh Bảo Duy

A thesis submitted to the School of Computer Science and Engineering
in partial fulfillment of the requirements for the degree of
Bachelor of Information Computer Science

Ho Chi Minh City, Vietnam
Year 2022

A RESEARCH ON RECONSTRUCTION AND VISUALIZATION OF 3D OBJECTS ON VR APPLICATION

APPROVED BY:
Assoc.Prof. Nguyen Van Sinh

THESIS COMMITTEE

ACKNOWLEDGMENTS

It is with deep gratitude and appreciation that I acknowledge the professional guidance of Assoc.Prof. Nguyen Van Sinh. His constant encouragement and support helped me to achieve my goal.

My gratitude goes to the other members of the research team, Mr. Tran Khai Minh and Mr. Nguyen Vu Duc Lam. Their technical help and encouragement as well as collaboration made these years a great learning experience. I am grateful to the faculty of the School of Computer Science of the International University, especially of Assoc.Prof. Nguyen Van Sinh for his support, guidance, and feedback since the beginning of this project. Gratitude is also expressed to the members of my reading and examination committee.

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ABSTRACT

The research of digitizing real-world objects into data and reconstructing them in a virtual world has been made more advanced by the emergence of VR technology. An utterly immersive and realistic virtual environment is close to being achieved from the fast-developing fields of computer graphics, geometric modeling, and computer hardware. The essential process of this technology is the reconstruction and visualization of objects in real life and simulating them digitally. This paper conducts in-depth research on this process and applies the knowledge obtained to building a Virtual Reality app which simulates a real museum for artifact preservation as well as showcases Vietnamese heritage. This study includes the following steps: research on the different methodologies of converting real world objects into 3D, specifically VR, benchmark their effectiveness in terms of speed, storage space, quality, ease of conversion, equipment involved, ect…, compare these results in experiments, proposing ideas to optimize and improve the methodologies during the process.

CHAPTER 1

INTRODUCTION

1.1. Background

The market for VR/AR has high potential and the future is in digitalization. The virtual world is becoming more accessible for people with the advancement of technology. VR gaming and software is at the forefront of technology with the Metaverse, and many more applications for daily life such as VR shopping, VR meetings, VR designing, archeology, ...

One big point of VR is the ability to digitize 3D objects and put them into VR, where users can not only see but also interact with these objects, completely virtually at a high resolution and realism without the need of them being physically present. This technology is still maturing with countless use cases which include virtual environments, artifacts and landmark preservation through digitalization, immersive entertainment experiences, prototypes for design and creative workflows, … All these functionalities rely on the accurate and effective reconstruction of 3D real world objects into the virtual world.

Given that the field of VR technology is receiving a great number of investments as it matures, there will be high demand for high quality imaging and modeling in VR, especially in the future when integration between real life and the digital world becomes more immersive.

One trending field in VR research is to simulate and re-construct a digital environment through data. This method allows the user to be immersed in a new environment using the power of Virtual Reality. Application of this technology can be applied in many areas: life-like communication and interaction with VR meetings, traveling and tourism, digital museums, ... This paper aims to apply this goal and functionality of VR into preserving and showcasing a digital museum and let users interact in close proximity with high quality model artifacts.

Preserving valuable heritage and artifacts is a powerful use case for VR, this requires research into many fields such as computer graphics, geometric modeling, image scan and processing, 3D objects programming, VR interaction and visualization, ect.. As the artifacts no matter how well made can be damaged and corroded or lost with time, this approach besides helping to showcase artifacts but also help to preserve and secure them for research and development far into the future where the physical version of the artifacts may not exist anymore.

1.2. Problem Statement

The cultural heritage of Vietnamese people resides not only in their cultural beauty but also in their invaluable artifacts. However, with time and many harsh events such as bad weather, the war, inadequate preservation or security, important heritage and artifacts may be damaged or lost, so future research and development into these culturally significant objects cannot be conducted. Digital data and information are much more resistant to the negative effects of time, it can be transferred and copied easily, making it one of the best mediums to preserve and secure important information. Thus, reconstructing cultural artifacts digitally will provide means for future research to be conducted lest those artifacts become stricken with unwanted circumstances.

Furthermore, some artifacts are incomplete upon discovery or as a result of the transportation and handling processes. Utilizing the remaining available materials, restoration of the artifact can be done to a certain extent with the aid of VR-based technology. With more and more historical artifacts being discovered at any time where upon discovery, they are immediately at risk of damage or loss. The Book of Kells, an artifact from the 9th-century, whose pigmentation on a minor part was affected due to transportation ("Book of Kells is damaged", 2000). Mesopotamian clay pieces were part of a number of looted Iraqi artifacts that were smuggled to the United States during the Iraq war (Arraf J., 2021).

In reality, a large number of artifacts are mishandled, destroyed or lost where it is highly impossible to recover. In order to prevent the above-mentioned circumstance from happening to artifacts discovered in the future, digitally modeling them once they are found will help improve preservation. Despite not being applicable to the direct prevention of damage and loss, the study on 3D modeling these objects will aid in the restoration and continuation of their research.

Besides its usage in archeology and preservation, reconstruction and visualization of objects are also researched for its industry market value. Services such as VR entertainment, virtual meetings, creative products made easier by the use of VR such as decorations, art pieces, sculpting, design and architecture, ect… all rely on the usage of real-world counterparts in the VR environment. A big part of the VR market at the moment lies in its ability to give users a realistic experience in another location without leaving their homes, VR tourism and exhibitions are effective avenues to apply techniques in object reconstruction and visualizations.

With many uses and applications of VR as stated above, an effective and efficient method to scan such objects and convert them into data to be reconstructed in VR is the most crucial step in any preservation or simulation purposes. The 2 most advanced methods of generating this data from objects are: LiDAR (Light Detection And Ranging) scans and photogrammetry, these two methods generates the point cloud which is a set of points in space that represent the surface of an object, and from such point cloud a mesh and texture can be created to make a 3D replica of the object.

The progress on VR hardware and software has grown dramatically from its inception, however there are still limits on how smoothly the VR headset can run - measured in FPS. Low FPS can make VR experiences feel jittery, breaks immersion or even cause motion sickness, so this study also researches into optimizing 3D models from objects both speed wise - the time it takes for the object to be rendered and simulated in the environment and space wise - the amount of space a 3D model takes on the storage device.

1.3. Scope and Objectives

This paper is a research into the method of reconstructing and visualizing objects into VR applications. We will explore the pipeline of converting objects into 3D models (point clouds) and uploading the constructed model into a VR application in an effective and optimized manner. The final scope and objective are to outline and execute a process of developing a VR museum environment. Research sources will include cross referencing other research papers, conducting experiments, documentation of relevant sources and software, and experience from professional experts in the relevant field.

Firstly, this paper aims to create a streamlined process in creating and visualizing 3D objects models into the VR environment by building an app using the Oculus Quest 2 to demonstrate. With methods to add interactions, optimizations, the environment setup process, etc. are showcased along with the data model collection phase.

The conclusions drawn from this paper includes the flow of creating, importing, optimizing, coding, polishing and many other processes in between of the development process of a virtual museum exhibition with accurate and fully interactable artifacts. Many other valuable techniques such as mesh cleanup, optimizations, applying geometric and computer graphical algorithms, for a high quality and immersive product.

The hardware included in this research is as follows: Meta Quest 2 VR headset, formerly Oculus Quest 2, the most popular VR headset on the market currently (Alsop T., 2022), personal computer powerful enough to do calculate and generate 3d models from the scan data (Intel i7 12th generation, 32gb ram), various 3d scanning medium: Einscan 3D scanner, commercial mobile phone without LiDAR, commercial mobile phone with LiDAR, ect,...

The software used to create and implement 3D models and programs: Visual Studio Community 2019 for IDE, MeshLab and Mesh Room for 3D model editing and rendering, Unity Engine and Editor for implementation and building application to VR, Oculus software, proprietary 3D scanning software on the scan devices.

In the scanning process besides coming to conclusions about the quality of scans between the methodology, this study will also provide optimization and techniques to remove noise and clean up the resulting model to make the resulting 3D object as high quality as possible.

1.4. Assumption and Solution

This research has high applicability. Future researchers can reference this study to determine the most optimal way to generate 3D data for their work, balancing quality between cost and time investment.

The market for digital museums and tourist attractions (Museums go digital to survive pandemic, 2021) increases the demand for scanning effectively and producing high quality objects in the Virtual Reality realm. This research will aid in that demand by outlining a step-by-step process from scanning to uploading to implementing objects into VR applications. Not only can museums showcase all of their collections which may not be possible to be displayed in their physical form due to limitations, it also helps in preserving the objects in the long run, allowing users in the far future to appreciate and study these heritage artifacts.

Assuming there is a research group or an aspiring gallery owner wanting to open their own Virtual Reality exhibition with the goal of preserving artifacts, showcasing cultural heritage, or for scientific research purposes, there will be many challenges in their way to execute this idea. There are many options when it comes to scanning objects, how to scan objects effectively, which is the least expensive or outputs the highest quality or something in between, the comparison made in this paper will give some insights and provide information on their decision. Furthermore, the instructions in this paper will also prepare them with knowledge on the following steps of the process such as importing point cloud, cleaning up the model, exporting to a development engine, and finally building a VR application with such models.

1.5. Structure of thesis

The structure of thesis is divided in 4 phases of the study:

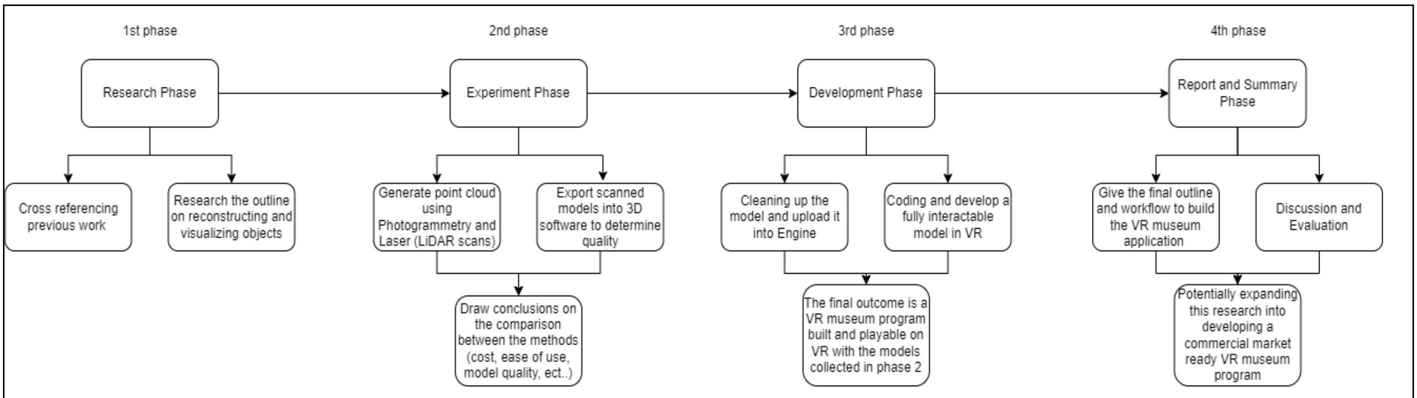


Figure 1. Chart structure of the thesis

Research phase:

- Other research on VR and model reconstruction is analyzed and referenced for more in depth understanding on the subject. Lessons and techniques are then extracted and used in the next phases.
- Get a complete understanding on the modeling and rendering pipeline process for 3D objects to make the further stages more streamlined.

-> Goal of this phase is to research and thoroughly understand the frameworks, the tools, the models and methods of scanning and reconstructing VR objects as well as learning how to develop a VR application.

Data collection phase:

- After gathering adequate equipment and information on relevant subjects, various trials of object scanning will be conducted using the primary forms of scan: Laser /LiDAR scans, with data taken using specialized tools (3D scanners)
- The scans are then exported into modeling software (Meshroom, Mesh Lab) and cleaned up for use in application.

-> Goal of this phase is to collect data on the models and generate an adequate point cloud of the artifacts/structures to be used in the development process of the study, as well as attaining some lessons on 3D scanning techniques, limitations, 3D model cleaning and optimizing, ect..

Development phase:

- The model created from the second phase is then used to make a VR museum experience.
- The final scope of the software is to make the objects fully interactable and viewed in high quality.

-> Goal of development is to create a functional and efficient APK file to be imported into VR headsets (Meta Quest 2) and let users view and interact with scanned models.

Report and summary phase:

- The final process of scanning and creating VR application is outlined, a step-by-step summary on how to scan, the best way to scan, price tradeoffs, final comparisons are made to create a streamlined and easy to follow process.
- Final evaluations of the research and future plans are outlined.
- The final product is showcased and to gather feedback.

CHAPTER 2

LITERATURE REVIEW/RELATED WORK

2.1. Related works on reconstructing objects into 3D environments

Paper: “Reconstruction of 3D digital heritage objects for VR and AR applications” by Sinh Van Nguyen et al. [5]

This paper covers the topic of digitizing heritage objects for the purpose of artifact preservation. Applying technology and knowledge from computer graphics, geometric modeling, and computer science algorithms, the research proposes a novel way to build and restore tangible heritages from 3D scans. Their final product was to build an algorithm to restore holes on the mesh of the object along with building a simple Virtual Reality museum. This research partly builds on that project in terms of recreating the Virtual Reality museum environment but with many enhancements including intractability, performance, quality, UI/UX, ect… This study also introduces the novelty of comparison between different scanning methods and their tradeoffs whereas this paper uses the single 3D scanner for their point cloud generation procedure.

The flow chart for the VR application process from 3D scans in this study:

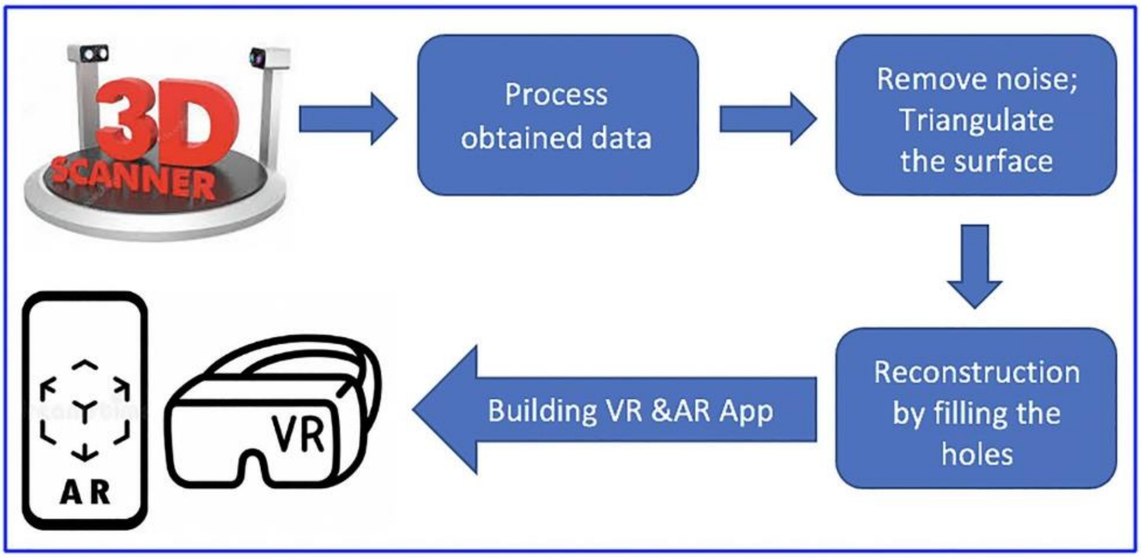


Figure 2. Flow chart of converting objects into VR/AR

The important step of this study is the reconstruction of meshes suffering from missing surface or holes with an algorithm better than existing simple methods such as close hole function in Mesh Lab, their method combines many previous studies (finding holes on triangulation surface [6], restoring methods [7], ect.), the algorithm calculates in a ring pattern starting from the boundaries of the missing surface and then moves towards the center, filling in the hole in the process for larger hole diameters, for small holes, the algorithm calculates the center triangle with appropriate normal vector and reconstructs simple triangles from that normal vector.

The research product of the study is to implement VR/AR applications for the purpose of showcasing and preserving heritage along with allowing viewers to experience Virtual Reality museums from their home in the times of Covid-19 and possible damages to the heritage objects because of the past Vietnamese wars, the passage of time or harsh weather conditions.

Successfully building an android APK to run on a standalone VR headset without connection to a powerful PC and an interactive AR application on the mobile phone to show information on objects and allow viewing of artifacts.

2.2. Paper review on reconstruction of heritage

Paper: “New opportunities of low-cost photogrammetry for culture heritage preservation” by Roman Shults [8]

Photogrammetry is defined as the science and technology of obtaining information about physical objects through the process of recording. This technology is the traditional, long tested and relatively cheap method of obtaining physical shape information of objects and environments, it is highly cost-effective with many free solutions with readily available hardware making it one of the best ways for beginner 3D modeling from real world objects. This study by Roman Shults presents a comparatively low-cost project of reconstructing in 3D the historical defense facilities from the World War.
The main source of data for photogrammetry software are photographs, the quality of the deliverable is highly dependent on the quality and the quantity of pictures provided to the software. To optimize for cost, the pictures taken for the photogrammetric process is from a smartphone, which is highly accessible and attainable for most individuals with 3D scanning needs, the hardware used is smartphone MEIZU M3 Max ($200 at the time of writing), and the software for photogrammetric modeling is AgiSoft Photoscan. To ensure the images taken are the highest possible in quality and compatibility with the software, a calibration step was taken, using example test objects, some parameters was adjusted and optimized: focal distance, principal point coordinates, coefficients of radial and tangential distortion, affinity coefficient, after errors and quality are in line with requirements, the modeling phase was conducted.

Figure 3. One of the sites modeled in this research.

With various objects recorded through photographs from the mobile phone, with large enough sample sizes (first object: 62 images, second object: 45 images, third object: 94 images), additional statistic information was recorded such as height, distance, slopes to aid in the modeling process and as a target for accuracy for the final product.
After the work was carried out to generate the 3D model in software, further testing was done to determine the accuracy between the measurements and the final results, and it was found out that the errors were in accordance with the requirements for the inventory of the historic

structures. In conclusion this research project about photogrammetry and its application were successful in proposing a cost-effective and feasible for non-organized or well-funded individuals or teams, compromising speed of data gathering and model quality (still within error limits) for accessibility and cost.

2.3. Paper review on methodology and outputs of 3D scanning and reconstruction

Paper: "3D Digitization and Its applications in Cultural Heritage" by Renju et al. [9]

The paper in Review 2 reviews the most common approach to reconstructing objects in digital from which is photogrammetry, however another method is also available with a higher threshold for entry which is 3D scanning. This paper in review 3 presents a 3D digitizing pipeline using this approach of 3D scans, applying to the field of cultural heritage preservation and research. By using 3D technology, both geometric and texture can be recovered, enabling digital archiving, virtual restoration and exhibition of museums and artifacts.

Proposed 3D digitizing pipeline:

1. 3D Scans process:

Comparing different 3D scanning hardware leads to some interesting conclusions at the very beginning, for large scenes, time of flight scanners can capture 3D information very quickly, however this comes at the price of model quality and texture, with errors up to sever millimeters, for works requiring further precision of the models, a more accurate scanning machine was used - the structured light scanner.

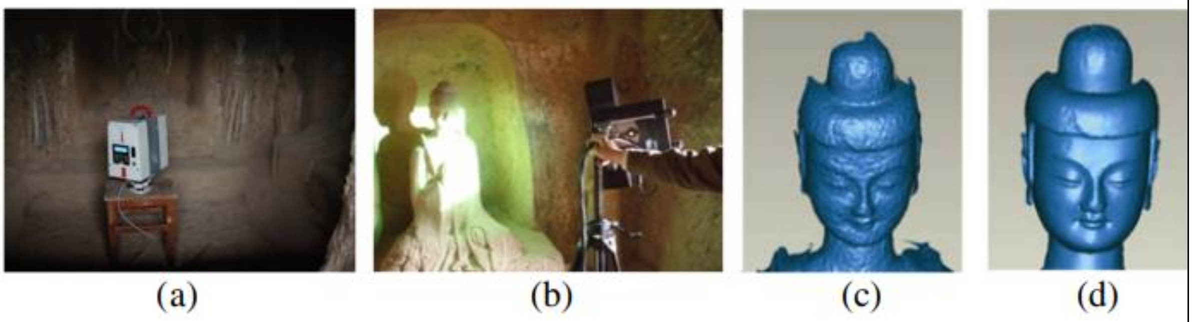


Figure 4. The structured light scanner (figure d) gives higher quality in both texture and mesh compared to the time-of-flight scan model (figure c).

2. 3D Registration step:

After the scans are generated, the next phase is the 3D data registration step, there are many challenges encountered in the study, such as: the structured light scanner gives higher quality but since it is limited in the area of scan, so to scan a large scene it takes hundreds of scans, thus errors are compounded which yields high inaccuracies. Registration is the step of matching the dimensions and transforms of the scanned environment, referencing existing work, one popular and practical method of multi-view registration using feature points based on the structured light scanners, which yields efficiency in time and ease of implementation. This method consists of setting up markers or some image features from the scan to determine the 3D coordinates of feature points, next they build the global frame for all the feature points, finally the registration step is carried out, appointing each point in the point cloud to the global frame.

3. Geometric modeling step:

This step combines and connects the point cloud data which consists of discrete points on the surface of the objects into continuous meshes, creating polygons and forming the shape of the model. With a mesh model instead of the point cloud data, representing the object in a more visual and easier to edit format, various geometric modeling and computer graphic techniques were applied to clean up and optimize the mesh. Algorithms such as Marching Cubes [10], Delaunay triangulation, polygon decimating, occlusion, hole filling algorithms, and so on were applied to create a fairly optimized and solid mesh.

4. Texture mapping step:

The final but very important step to give the digitized model the realistic look is to add textures and colors. This means mapping and assigning high quality photos or textures to the surface of the model from step 3, each vertex on the mesh not only having the 3D position but also a 2D coordinate system corresponding to the texture image.

Furthermore, this paper also outlines some potential and current use for 3D modeling technology, specifically applications in the field of archeology and cultural heritage study:

- Digital Archiving: the finalized models and textures of the digitizing process can be captured and permanently preserved.
- 3D Line Drawing: line drawings are essential components of the archeological report and research, depicting the artifacts in 2D outlines, similar to sketches.

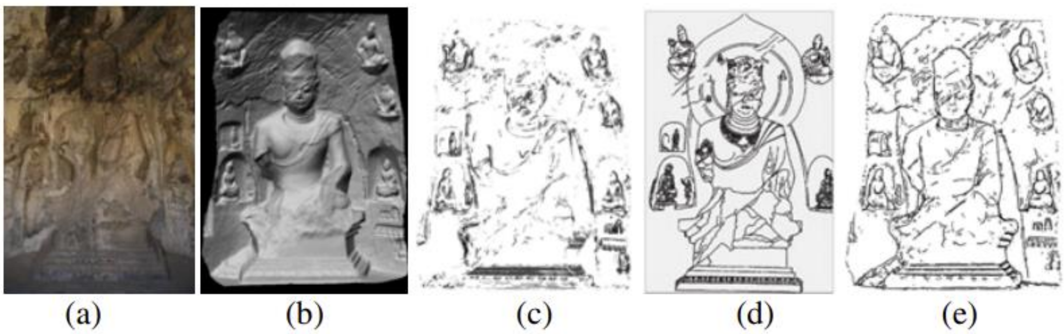


Fig. 4. 3D line drawing for a Buddha in Longmen grottoes. (a) Photo of the Buddha. (b) 3D model. (c) Local scales. (d) Manual drawing. (e) Multi-scale ridge detection.

Figure 5. Comparison between representations of the 3D model

- Virtual Restoration: Using various algorithms from computer graphics and geometric modeling, classifying missing parts and determining appropriate restoring algorithms covered in review 1 is also vital in assisting in preservation efforts, beside computer algorithms, reconstructing broken or missing parts of artifacts are also carried out by adding the missing polygons by software manually, taking reference from more complex sources such as descriptions, paintings, ect.. where computer algorithms could not analyze and recreate effectively.
- Virtual Display: Showcasing fragile or sensitive artifacts publicly could endanger the objects by exposing it to the elements, risking harm or it being stolen, ect… thus the virtual display solution solves this critical issue by allowing audiences to enjoy the objects from many viewpoints with closer interactions than real world exhibitions would allow.

2.4. Paper reviews on building 3D applications

There exists many scholars works contributing to the process of reconstructing and remodeling real world objects and sites in 3D, for purposes of gamification, attracting and expanding interests of people, for preserving and documenting artifacts for research, this section is dedicated to the review and cross-reference of these studies. These papers contain vital information documenting the scanning process, evaluations of scanned point clouds, applying the models in applications, processing of meshes that we could benefit from in this study. From the references this study will take advantage of and catalog all the useful information provided and potentially apply the lessons learned in future chapters.

2.4.1. Virtual museum in Malaysia

Three-dimensional recording and photorealistic model reconstruction for virtual museum application–an experience in Malaysia by Wei et al. [11]

Summary: This 2019 paper is the detailed analysis of the process of digitizing into 3D environment the heritage site A'Famosa fortress and the Bujang valley Archeological Museum in Malaysia. The paper's scans were separated into 2 categories: archeological artifacts - objects, and historical buildings recordings - environments. Equipped with specialized scanning equipment, the team successfully mapped the environments and objects with photo realistic accuracy and detail.

The article categorize the scanning process into the following chart:

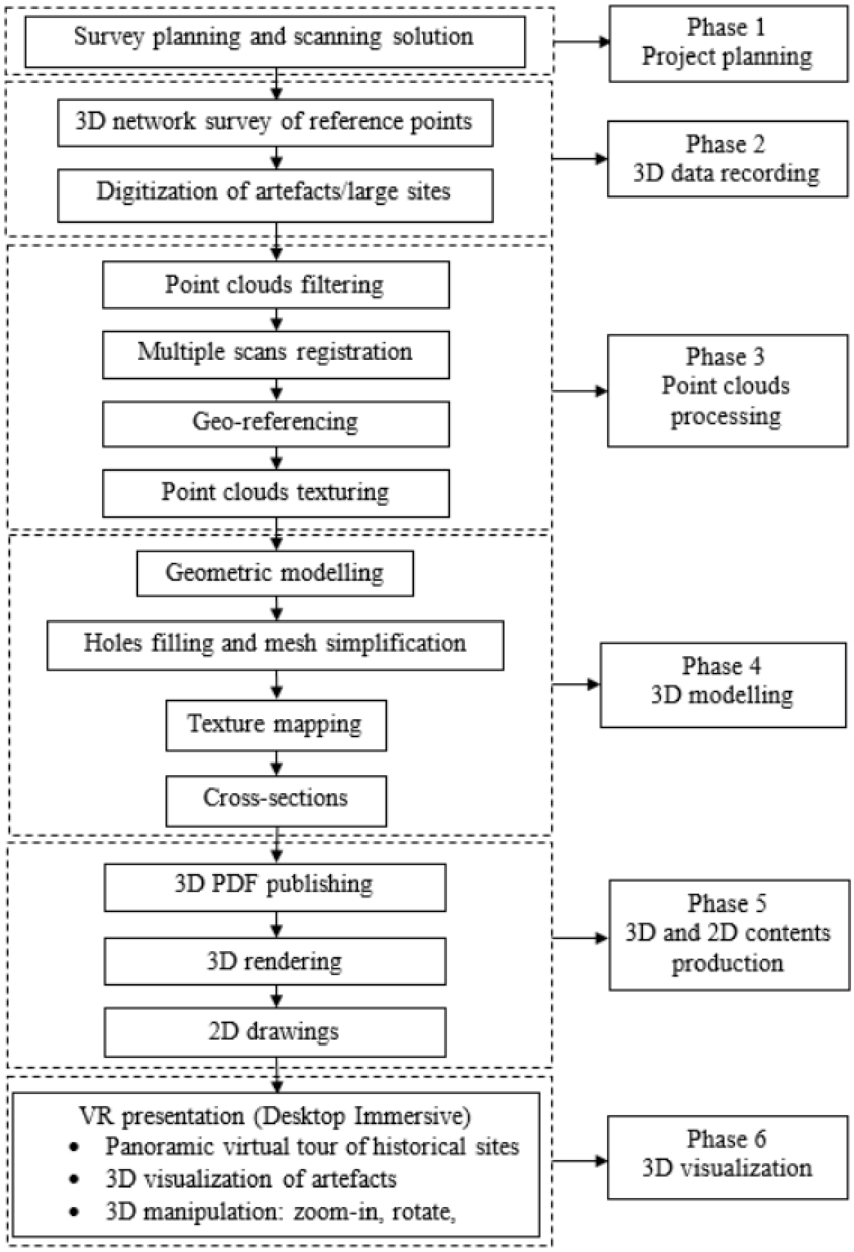


Figure 6. Full workflow chart of the digitization process

This research will simulate the above process flow but with the intent to measure and compare the effectiveness of different scanning methods, which is a novelty because Wei et al. used specialized and expensive (prices at the time of writing) equipment for their point cloud generation: FARO Photon 123 (5000 USD +) for laser scanning, Nikon DSLR D300s camera (400$ USD+), Konica Minolta Vivid 910 laser scanner (7700 USD+), these equipment's are very high cost and cutting edge, allowing them to create very high quality scans and measurements from the color texture to the 3D shape of objects and environment. Whereas this project aims to develop and implement as well as optimize the resulting meshes of the scanning process and integrating them into a virtual museum environment offering high immersion and great educational value.

2.4.2. 3D reconstruction and gamification for educational purposes

Using different ways of 3D reconstruction of historical cities for gaming purposes: The case study of Nafplio by Antonios et al [12]

Summary: This is another research focusing on the reconstruction of historical buildings and environment. However, this case study details more on the gamification and application development flow than the process of scanning and generating 3D meshes and models. Showing how the 3D visualization technology has developed throughout the times, showcasing many projects aiming to reconstruct old heritage for preservation and education, this article establishes the many use cases and benefits of 3D reconstruction efforts, analyzing and listing out many advantages as well as challenges.

Nafplio in the 19th Century educational 3D game case study:

The historical city Nafplio in Greece has many significant traits of cultural characteristics were the spotlight of the 3D educational game: http://www.pli.gr/en/content/19th-century-nafplion, by gamifying the academic component, the historical education and learning aims to attract and engages a larger audience of students, supporting their knowledge and background on the first capital city of Greece. Based on the original browser-based game, the authors then developed a larger scale 3D application using the foundations and models of the game. With values such as restoring and comparing the city in different time periods, exhibiting buildings and constructional changes throughout the centuries, using materials such as images, drawings, descriptions for non-existing monuments.

Their production pipeline for the development of the 3D application is as follows:

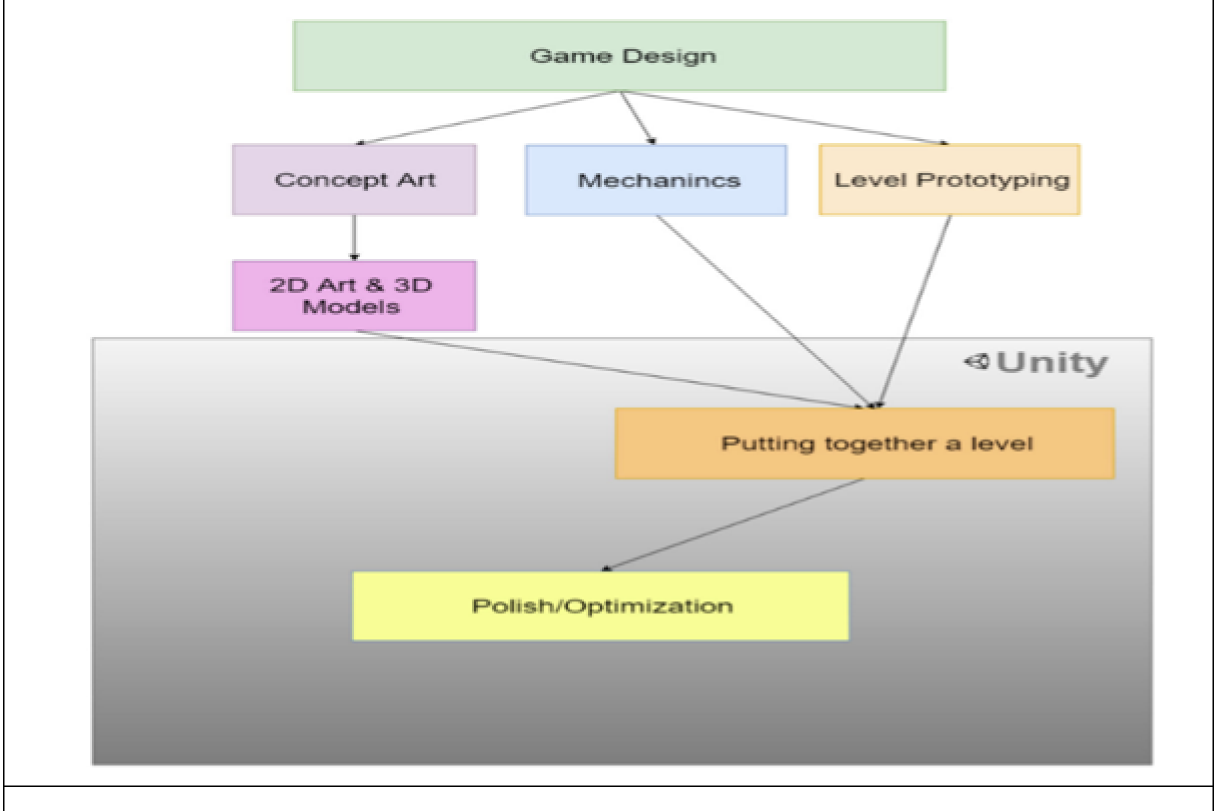


Figure 7. Antonios' research project workflow

This process is similar to the development flow of video games, since the purpose of the project is to create an educational app in a more gamified approach to appeal to broader audiences.

This scientific paper is a case study, so the academic value lies in the analysis and the conclusions drawn from the study. The resulting 3D application/ game establishes and builds from the idea that 3D reconstructions of historical places are a crucial aspect of cultural heritage preservation and research, from evaluating characteristics accurately to allowing such information to be re-used, expanding the potential uses and broadening the audience of historical and cultural values.

2.4.3. 3D heritage digitization and workflows

Preserving heritage sites using 3D modeling and virtual reality technology by Salsabil et al. [13]

Summary: This paper also describes the manner of reconstructing heritage sites from VR technology using 3D modeling. Instead of trying to take the most accurate snapshots of the heritage sites using 3D scanning and point cloud generation, this study obtains the 3D models of historical environments by re-creating them in 3D software, in this case 3ds Max.
Besides the development of VR applications for preservation of historical heritage establishments of Dhaka city of Bangladesh, this research also experiments on different scanning techniques and VR game development. The main focus being to create a digital archive similar to an online museum in that it allows the preservation and storage of the essence of the heritage, not physically but informationally through 3D models and textures.
The following steps were taken to measure the cost-effectiveness and accuracy of three-dimensional depth of objects:

1. 3D Modeling:

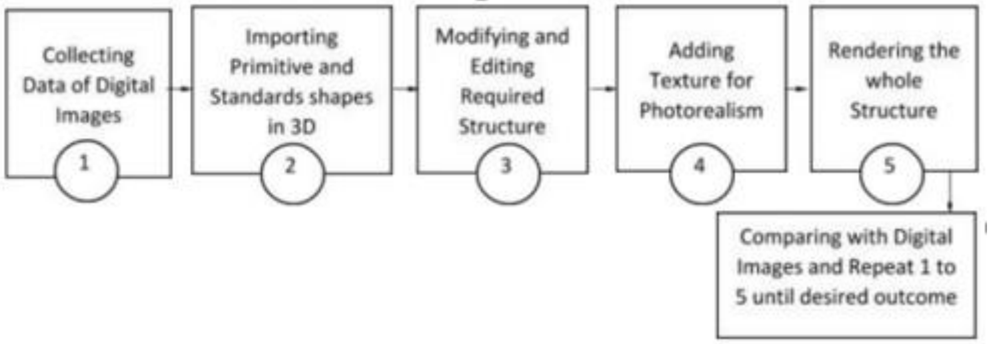


Figure 8. Block diagram of the proposed 3D modeling using 3DS Max.

The research opted for an implementation approach to reconstructing the subjects. First high-quality images were taken at many different angles from eye-level to 360 degrees, with these pictures as a reference, a complete model was built from scratch using Autodesk 3ds Max software, with foundations for buildings being primitive shapes like box, cube, spheres, ect… With faithful recreation using the images, the models successfully capture the appearance and characteristics of the real-world counterparts.

2. VR Application:

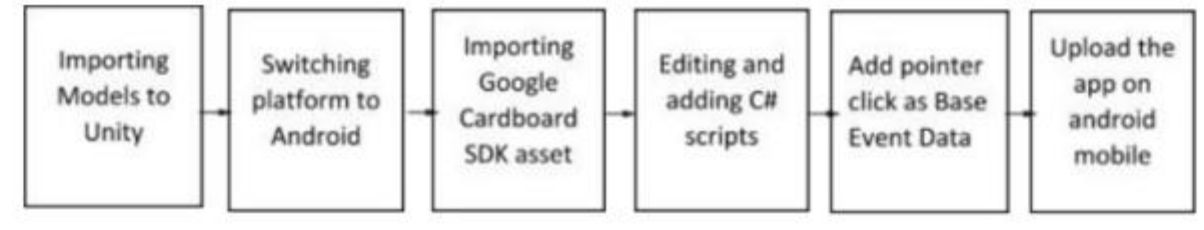


Figure 9. Building a VR application on the Unity3D engine

Using Unity which is a power game engine, the VR application was implemented with many functions and interactions. With the resulting 3D models from the first step, a VR ready environment was created. For platform choice, the study adopted Google Cardboard which is a very budget VR system with no hardware embedded but using the processing power and display of a mobile phone to present the VR view and using gyroscopic and motion sensing built in the device to support player head movements and control.

3. Digital Archive:

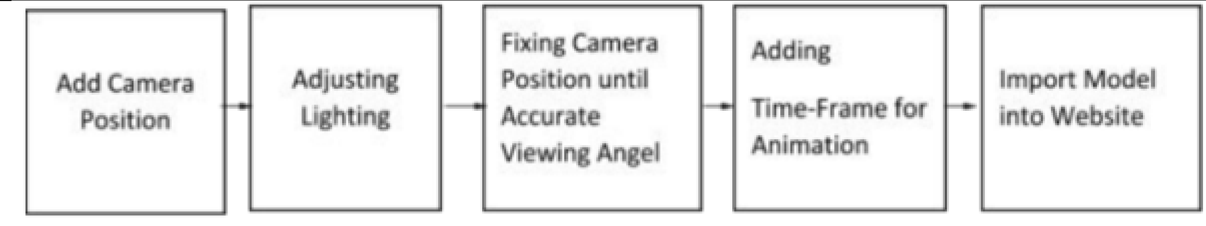


Figure 10. Implementing 3D models into the Digital Archive

Besides developing a VR application allowing users to view the objects in a real and interactive way, this study proposes a online archive for the models created and potentially other 3D objects for preservation and sharing, hosting the models in a server allowing the products to be viewed and accessed globally, expanding the reach and ease of use for individuals who doesn't have the means to access the sites in person. This database also is an avenue to crowdsource the preservation and increase awareness of historical value.

Experiments and Conclusions:

Some explanations for their choice in the method of attaining the 3D models of the heritage structures by re-creating the model by hand instead of using some other approach such as photogrammetry or 3D scans are as follows:

- Since the paper aims for inexpensive preservation and application development, the most cost-effective way to get 3D models without much monetary investments is the process of modeling the meshes from reference images.
- As their VR applications are designed to be mobile ready (to be compatible with Google Cardboard), as the processing power of a phone CPU and GPU are limited and taking into account battery life and user experience, the model and meshes have to be as low poly and relatively simple to render. So by constructing the models by hand, it can be optimized and customized to a higher degree to ensure optimal performance and adequate accuracy.
- The scope of the research is to visualize and implement a large building structure(s), photogrammetry would take immense effort from the data collection phase - taking pictures, ensuring accurate lighting, multiple angles, ect.. to the software clean up phase,

such as correcting meshes, optimizing, and much longer development time to clean up and output the finalized model.

- With many limitations of 3D scanning present, such as scans taking a significant amount of time and requiring a static environment and powerful hardware, busy areas like heritage sites are difficult to be scanned without a big budget and organization. Furthermore, cheap scanning equipment often gives inaccurate or low-quality results, making the polishing phase longer and more challenging.

2.5. Review on real world applications of 3D reconstruction and visualization

This section explores the future and current uses of 3D reconstruction and visualization technology, as the functions and benefits of recreating real-world environments and objects does not stop at entertainment and virtual tourism. Building on the foundation of reconstruction and visualization, models and meshes from the 3D can be applied to many fields ranging from education, medical, space science to entertainment and creative design, being aware of these utilizations emphasizes on the importance and instrumental value of this study. As generating 3D models either by 3D scans or photogrammetry or any other methods is a vital facilitator for many advancements in human science, this section of the study will attempt to substantiate the relevancy of three-dimensional reconstruction and visualization.

2.5.1. 3D digitization in law-enforcement

A study of 3D digitization for Crime Scene Investigation by George et al. [14]
Traditional crime scene documentation majorly consists of taking pictures, taking samples, video tapes, measurements and other mediums, however one such means of reconstructing the crime scene which is 3D digitization is still underutilized because of challenges such as expensive equipment required and the specialist skills to operate such equipment. However, with the development of 3D scanning technology, the expertise required is being lowered and the scanning hardware is also becoming cheaper while increasing in scan quality. This paper summarizes and analyzes the usage of 3D digitization in crime solving and scene documentation.
The research team outlined the potential applications of this technology in crime scene investigations:

- The study, prevention and solve of crimes using the information prior or during the event.
- The analysis and documentation of the scene after the event.
- The recreation of the 3D environment after the scene is no longer available (for archiving, educational, research, ect… purposes) in VR/AR.

They also defined the conditions in which the method of digitization should be evaluated for, these applicability factors facilitate efficient and accurate reconstructions of the crime scene for further investigation:

- Technical constraints.
- Ease of use.
- Level of automation.
- Cost.
- Time duration.

The paper discusses various modalities of scanning and references many papers of investigations that 3D scanning, and reconstruction has been applied. For example: the reconstruction of a traffic accident [15], analysis of human skin and hair brush surfaces to determine if abrasions are from the hair brush [16], a scanner is used for scanning walls for

blood pattern analysis [17], reconstruction of the crime scene in a room [18],measurements and calculations of bullet trajectories as they hit drywall surface from different angles [19], scanning various household items to compare the shape to wounds to distinguish the weapon [20], ect… Such papers are the foundation to prove that 3D reconstruction of objects and scenes could be applied to law enforcement to great effect and could potentially be used to solve and prevent crimes.
Many practical applications of 3D scanning do not use a singular method of scanning and instead use a mix of several scanning techniques and hardware to maximize efficiency and quality such as pairing laser scans with photogrammetry. As the means to review the scanned scenes and objects, a large portion is simply displayed in the common monitor with mouse and keyboard interface, however, a more detailed and dynamic environment such as Virtual Reality allows for much more intractability and depth of simulation. This gives the distinct advantage of being much more immersive and detailed, allowing for deeper inspection and logical thought with the space [21, 22].
The authors pointed out such benefits to crime fighting that 3D reconstruction and VR technology will make more effective and present a new avenue to achieve goals:

- Crime prevention
- Analysis of the crime scene
- Education of stakeholders through VR representation.

This paper present the state of 3D digitization technologies from the view of crime and law enforcement, confirming the efficacy and applicability in these fields, recommending the hand held laser scanner after experiments and test to conclude that it's the most versatile and mobile while still achieving adequate scan quality, as for cost effectiveness the RGB-D scanner lies in between the photogrammetry modality and 3D laser-scans, allowing relatively easier use times and simplicity to specialized 3D scanning equipment while giving better results and computational power investments than the photogrammetry approach.

2.5.2. 3D applications in the medical field

3D scanning application in the Medical field: A literature-based review by Abid et al. [23]
The next implementation of 3D scanning technology is analyzed and presented in this literature-based review, researching various papers from 2008 to 2018, identifying and showcasing different scanning techniques and its impact, as well as trying to determine the best possible usage of 3D scanning technology in the medical field.
There exist many different types of scanning utilized in the medical area to obtain data on the patient's body from internal to external characteristics:

- X-rays: a scanning method taking advantage of the property of soft tissue not being able to absorb high energy rays do not present in bone, therefore x-rays can extract images of bones for diagnosis.
- Computed-tomographic (CT) scan: this scanning modality also uses x-rays It provides detailed information about the body such as the brain and its vessels, inner ear, eyes, sinuses, heart, lungs, neck, spine, shoulder, reproductive system and other inner parts of the body.
- Magnetic resonance imaging (MRI): using powerful magnetic fields and radio frequency pulses to get data on bone, soft tissues, organs... differentiating abnormal tissue for accurate diagnosis.
- Ultrasound: produces pictures of the body using sound waves, diagnosing swelling, pain and infections within the body. It has been used to aid in determining heart condition, guide biopsies and assessing internal damage.
- 3D scanning: The focus of this research, creating free-form accurate and high quality the dimensions, shape, texture, color and other external appearance characteristics,

distinguishing this method of scanning to other medical scans is that it is primarily used for external scans, whereas the modalities listed above serves to gather information on the internal elements.

Three-dimensional scanning has revolutionizing effects on many industries, and such effects are being seen on its contributions to the medical field. One major use case of 3D scanning is the design and production process of prosthetics, dental appliances, implants, with the accurate measurements from the scanning phase allowing for high precision dimensional and geometric data, furthermore the design can be simulated in 3D space of optimal designs without the need to manufacture test samples, with the created model 3D printing allows a cheap and exact recreation method for assembling the designed product.

Benefits of 3D technology in creating prosthetics compared to the traditional machining approach are as follows:

- Complexity: Usually taking days or weeks to complete the process from the design to the machining phase, whereas using 3D scanning and printing, quickly capturing models and having the virtual simulation to adjust the design accordingly speeds up the time and complexity of design.
- Time: By having quicker duration of implementation and manufacture, the process of iterative improvement and experimentation can be expedited and produce more effective results. In the situation concerning medical issues, ensuring success with less time with the medical tool is vital.
- Cost: 3D scanning and printing are used for custom and intricate parts that are customer specific, changing from patient to patient, these differences are accounted for during the printing process leaving little to no waste material.
- Data gathering generating data through the scanning process for easy cataloging, 3D models can be stored digitally and automated with high accuracy many dimensional and geometric information which would be difficult to measure manually.
- Multi-material prints: 3D printing and designing technologies allows for the printing process to be customized and set up so that a single print of a model can be made up of many different materials allowing for more comprehensive solutions such as parts of a bone requiring rigidity at different parts, whereas traditional machining this process means that the different parts need to be manufactured separately and assembled later on.

More specific use cases and examples of 3D technology being used to aid in medical systems are also reviewed and listed, the most notable instances are:

- Allows for designing and manufacture of components that are too small and complex such as electro-mechanical assemblies, catheter-like devices, ect…
- Data collection and achieving diagnosis on burn victims where direct contact is not permitted.
- Helping to treat, research and educate skin related problems such as bacterial infections, burns, wrinkles, ect…
- 3D image captured by the 3D scanner, it detects deformities through the analysis of the patient’s body shape, enabling interfaces and more tight fits of prosthetics and patient anatomy.
- In dentistry, three-dimensional scans are a crucial tool in creating plaster models of the teeth, silicone maxillofacial prosthetics and ceramic crowns.
- Replication in high detail of human structure for research and education purposes, 3D models of skeleton, muscle, cell structure, ect… can be reconstructed and visualized in 3D simulation.

In summary, researchers and technologists have been and will be taking advantage of improving 3D technologies in the medical field, integrating research and surgical/clinical practices holistically. There is extensive scope for application and development from generating high accuracy and quality model scans, which facilitate the designing and manufacturing of medical tooling and devices, prosthetics and orthotics such as bone replica, forensic scaffolding, tissue engineering, dental models, brace brackets and arch wires, removal appliances, occlusal splints, and many more medical apparatus. Besides the function in the creation of medical instruments, 3D technology allows for avenues in medical diagnosis, data collection, education, non-intrusive patient scans,

2.5.3. 3D Virtual reality in education

Virtual reality and Engineering education by Veronica S. Pantelidis [24]
The potential of the applications for virtual reality and 3D technology has been even before the 21st Century, this paper by Veronica S. Pantelidis from 1996 discusses the appliance of virtual reality technology in education and specifically in the Engineering field. Examples on how VR is used to teach military pilots using headgear with displays to simulate a space shuttle or aircraft, battles are simulated to explore outcomes and strategies, ...
An extensive listing of reasons to apply virtual reality technology in education and more specifically the engineering teaching process:

- Provides motivation: being more immersed and being able to apply VR technology contributes to increased motivation and interest in students.
- Being able to clearly illustrate features and processes from all viewing angles with great clarity, so such processes could be understood better than via other mediums like text or illustrations.
- Allows interactions with the 3D objects such as zooming in or out, seeing small details and the whole system dynamically.
- Enabling the disabled, allowing them to participate in experiments and demonstrations where they could not be part of otherwise.
- Gives insights based on new perspectives.
- Requires active interaction, this could make learners more active in taking part in the study rather than passivity.
- Provide an avenue for some subjects to be taught effectively online through VR and the Internet.

VR lets learners and teachers participate in academia in a way not not possible with traditional means such as textbooks and slides, they are put into a life-like simulation and experience the learning materials instead of just reading or watching a video. The benefits listed above contribute to a more effective learning experience with great clarity and appeal.
Specifically for engineering study where there are many difficulties and ways to improve on the teaching and learning experience, as opposed to testing and showcasing real world machinery for engineering lectures, VR lessons can be deployed to solve these challenges:

- Dangerous operation of machinery if the operator is untrained or unmonitored.
- Impossible machinery or processes to be showcased in person.
- Too inconvenient, time consuming or costly.

Figure 11. Application of VR in Haywood Community College in 1996

In conclusion, as technology develops and specifically three-dimensional virtual reality systems reduce in price and increase in performance and quality, its applications in education are fully realized and exercised, benefiting both educational institutions and learners in the academic process.

CHAPTER 3

METHODOLOGY

3.1. Overview

In this section, the outline of the development methodology and process plan is documented in detail. Requirement analysis is conducted to determine appropriate software functions, analyze tradeoffs and innovations to come to the final product design. The software development cycle is divided into 5 steps, where each step brings the final product closer and builds upon the previous steps in increments. Approaching the VR application from many technical directions such as UI/UX, ease of use for users, implementing features, expansive functionality, optimizations, software issues resolving, etc.
The methodology consists of 5 development steps according to the graph:

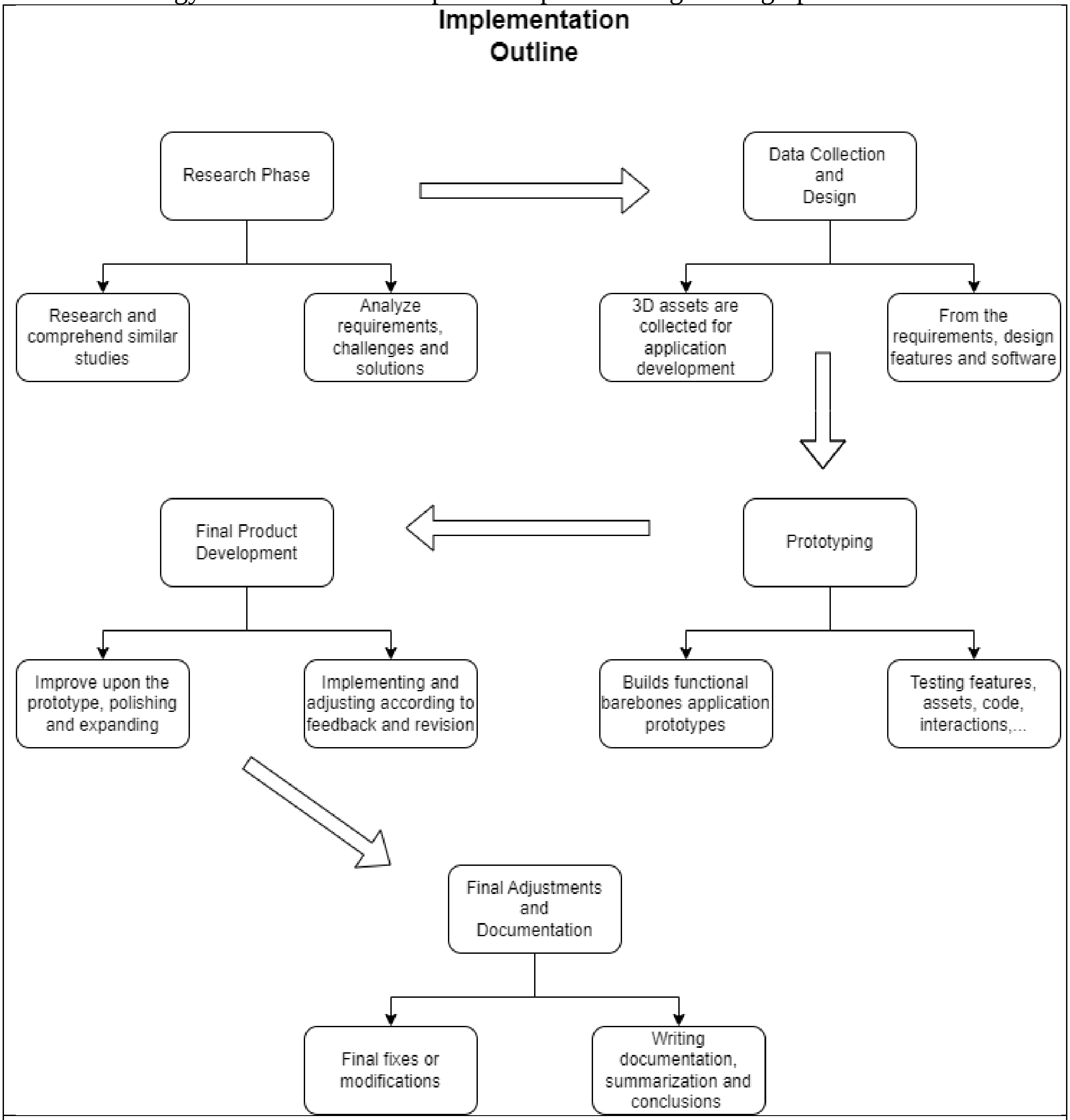


Figure 12. The flow outline of the implementation process

Chapter 3 of this paper will cover the first 3 stages of the product development cycle (from research to prototype) and Chapter 4 will cover the final 2 phases (final development and final adjustments).

3.2. Research Phase

Before any software development is started, the research phase is conducted to determine various user requirements as well as gather information and solutions to issues from similar studies or programs. Research methodology primarily consists of analysis and cross reference of scientific papers in the field.

The goals for this phase include:

- Draw experience from similar studies.
- Construct use case diagrams.
- Analyze requirements and feasibility of features.
- List out potential problems and solutions.

3.2.1. Lessons from similar studies

Many conclusions have been drawn in Chapter 2: Literature review, offering techniques and design concepts for the VR application. We will further look into some specific studies about VR applications from functional and technical perspectives.

In their research in VR-Museums, George et al. [26] concluded that there is demand and usage for VR museums in many use cases:

- Lack of space: many museums only display a small number of their exhibits because of limitations in display space.
- Rigid presentation: many precious artifacts are secured and guarded closely, allowing only surface level inspections for users.
- Reconstruction and visualization: VR technology could solve the issue of missing or damaged artifacts using reconstructions, limited access, sensitivity to exposure of exhibits, ...
- Creation of environments: allows users to visit restricted access sites, such as dangerous locations, warzones, ...
- Mobile exhibition: digitized content can be experienced remotely and can be carried mobily, offering access through the Internet or files.
- Navigational aid: Offering quick access to specific areas of the museum without physically traversing the space, helpful for users with disabilities.
- Design process aid: having a simulation of the space offers visual prototypes for design and evaluation of real-world museums without construction.

The VR Museum should be able to solve many of the above issues and offer appropriate functionalities.

Another study from Maria [25] states that there are problems to creating a VR Museum application, specifically interactive learning environments must take into account the physical context of the public space, support the conceptual and aesthetic standards of the learning purpose, and be functional and accessible to its intended group of learners.

Another problem arising is the accuracy and quality of the 3D scanned objects. The resulting mesh model could have errors in the scanning process such as holes, missed parts, ... This issue can be resolved using the techniques developed by Sinh et al [27] to detect holes using geometric algorithms and filling in the missing parts conforming to data in the local area of the missing surface to ensure accuracy and natural looking surface.

3.2.2. Use case diagrams

Specific use cases for the application are diagrammed to illustrate functionality and development requirements. The primary intended customers of this application are museum visitors and the museum organizations. This application must have functionality to not only support both the user experience but also the museum organization to have CRUD (create, read, update and delete) functionalities to support custom exhibitions and future expansions.

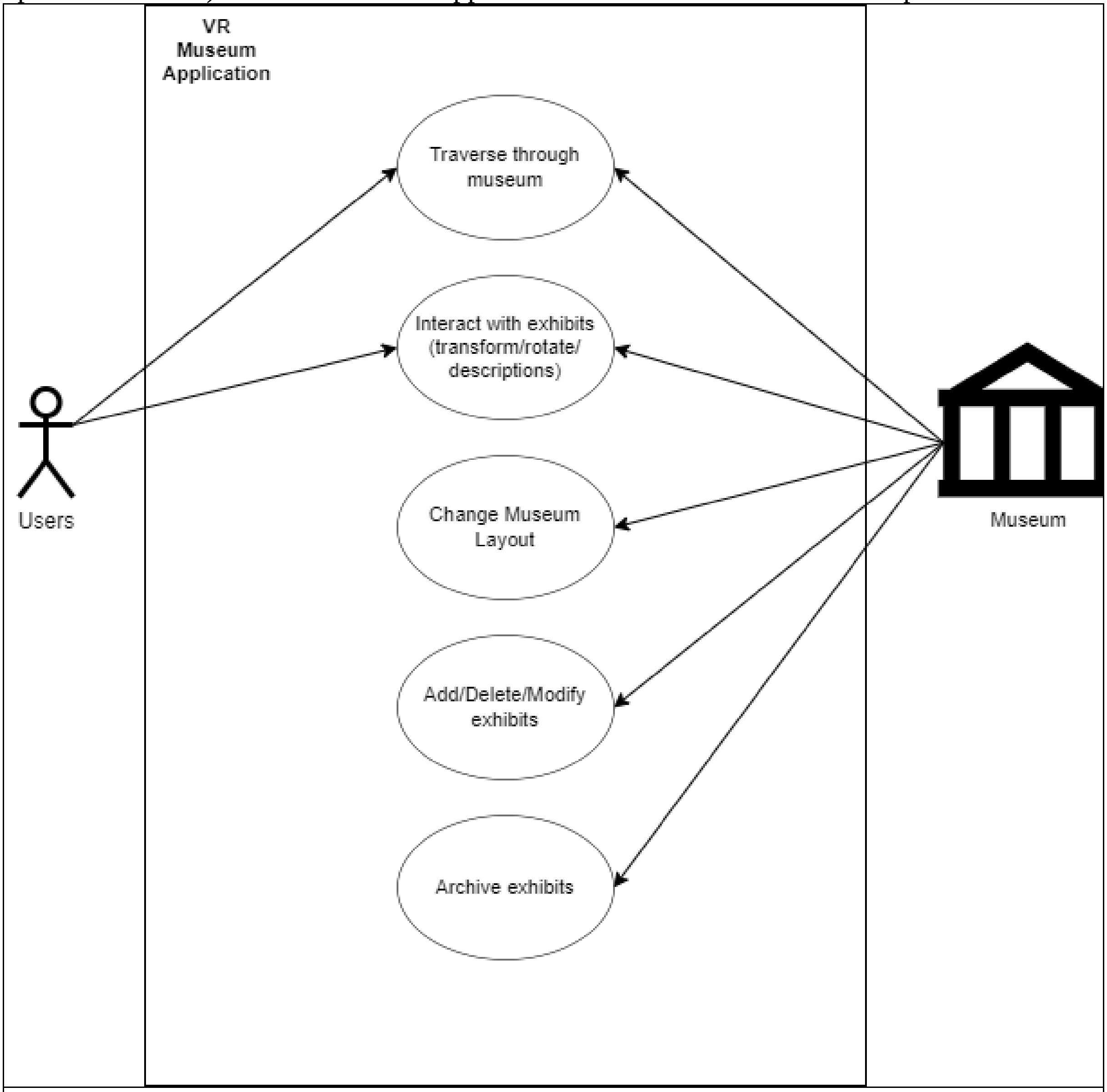


Figure 13. Use case diagram for the VR museum application

Here are the main functionalities and their detailed descriptions for the VR application:

- Traverse through the museum: There are 2 possible ways for the user to traverse through the simulated museum environment that is standard in other VR applications: Continuous movements and Teleportation, each with its own advantages and drawbacks. In this specific instance, for the main movement the Continuous movement method was chosen, this method allows users to simulate walking and turning realistically with the VR headset controllers, allowing for seamless and natural feeling exploration of the museum environment. The teleportation movement option is also planned for implementation for larger scale structures where walking to exhibits takes significant time.

- Interact with exhibits: This use case is the primary function of the simulated virtual reality over the real-world museum counterpart. In most museum displayed artifacts, museum visitors are prohibited from touching or interacting with the exhibits in any way, this limited interaction is not an issue in the simulated 3D world, where users can pick up virtual objects without causing harm to the real artifact, adding value to the museum experience. More specifically, the interactions with objects must be able to be executed with the hand controllers provided with the virtual reality headsets, so this will include movement and rotation, objects can be picked up and rotated in all 3-dimensional axes for closer inspection.
- Another benefit of Virtual Reality is that it is more customizable than the real-world environments, modifications such as architectural changes, switching heritage displays, ect. would require significant amount of effort and cost to carry out in real museums and risk the objects being damaged, whereas in the VR application, museums could change layout, re-design architecture, move exhibits... in a completely fluid and hassle-free approach. With the source code, virtual objects could be moved, resized, change elements such as lighting, colors, and only intermediate level IT knowledge is required.
- Extending the above functionality is to allow the museum to edit existing exhibits, this includes adding new artifacts, delete and modify artifacts, this is highly customized, museums can update descriptions, change the mesh models, remove erroneous exhibits.
- Museums should also be able to save exhibits for archiving purposes, archive created exhibits and export them to be reused with other research and applications such as web360, 3D printing, ect.

3.2.3. Requirement analysis and feasibility

With the core functionalities outlined in the above section, the requirements to implement such functionalities are listed to determine their applicability in the study's development budget and skillset.

Since this project is based on the most common Virtual Reality headset - the Oculus Quest 2 (Meta Quest 2), it is assumed that users of this application have such hardware to run the application, which includes the headset and 2 controllers.

General requirements:

+ A computer powerful enough to render 3D graphics and run them in the engine. For the development of this software, a computer with 12th Gen Intel core I7 CPU and Nvidia RTX 3080 with 32gb of DDR4 ram was used in the development process.
+ A VR platform for testing and developing: An Oculus Quest 2 was used to emulate user experience.
+ 3D Development software: The chosen game Engine for this project is Unity3D, a popular and robust system to create the VR museum.
+ Code development software: Other software development toolkits include Git for version control, VSCode / Visual Studio for IDE, C# and .NET frameworks together with Unity.

One of the goals of this study is to outline a step-by-step pipeline to create a VR environment, aimed towards general usage and research, so all of the above requirements beside the hardware are all relatively accessible.

All the use cases needed from the VR museum are all achievable within the Unity3D framework using coding and game design principles. In fact, there are frameworks available that aid in the development of the app, however these frameworks don't cover all use cases or provide them in separated features, so the development process aims to implement them into one package.

3.2.4. *Potential problems and solutions*

During the research phase, there are issues that are expected to happen during the development process, solutions to such problems are already planned in the research phase to ensure smooth and effective development.

Problem: Models for artifacts, and museum architecture are not available.

Solution: For the prototype, a system is built using pre-built assets from the Unity Asset Store, the store contains many assets which include museum prototypes, these mock models are used in place of real museum pieces which are easily added and replace the placeholder models.

Problem: Scanned artifacts and objects have missing surfaces during scans.

Solution: Using the algorithm from [5] and MeshLab software, we can adjust and fill in holes effectively in respect to the area around the hole, making the filled area natural and in accordance with the surface.

Problem: Museum scenes are complicated and high quality, causing stutters and lags.

Solution: With the Unity3D engine, various optimization techniques are available for large environments, such as GPU batching, static batching, occlusion culling, dynamic LOD, ... Also in the development process, algorithms and calculations are optimized for the best user experience.

3.3. Data collection and Design Phase

3.3.1. *Data collection*

One of the most crucial elements of the application is the visual elements of the virtual museum environment, as the goal is to simulate a real trip to the museum, the space has to be relatively accurate to real world museum infrastructures as well as the exhibits has to have sufficient realism. So, the data collection phase is carried out to learn about museum architecture, exhibit display standards, museum atmosphere, exhibition designs to closely emulate the environment and ensure an immersive user experience.

For data collection on museum architecture and artifact display standards, a field trip was conducted to the Ho Chi Minh City museum, the museum displays heritage of the Vietnamese culture which spans thousands of years.

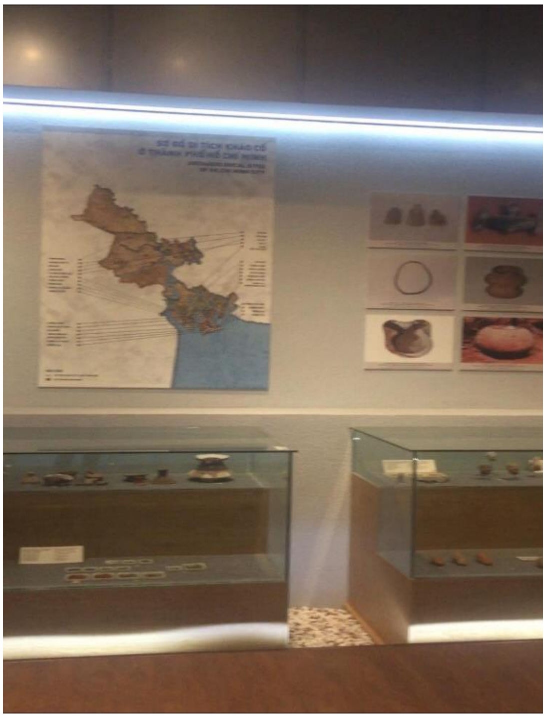


Figure 14. Historical Wine Jar from the early XX Century.	*Figure 15. General museum displays.*

The architecture and displays from the museum will serve as a reference point for the museum architectural model in the application, with modifications to suit the virtual reality experience, adding functionality such as Virtual text, UI, interactability with objects like closer inspections, rotations.

As for the models of the 3D objects, scanning methodology is applied to convert and digitize the physical objects into 3D meshes for usage in the application, using laser scans from specialized tools.

Figure 16. Scanning museum artefacts, using EinScan Pro HD laser scanner

The 3D model scans are then processed using EinScan proprietary software, as well as Meshlab to clean up, optimize and enhance the models through methods such as hole filling, vertex reduction and color information is also recorded and included in the resulting mesh. The meshes are then exported into .OBJ format to be readable and can be integrated into Unity3D environments.

3.3.2. Application design

Ensuring user experience and the game flow of the application is also an important factor in creating a user-friendly and intuitive software product. Despite the purpose of this application being mainly to aid in research, academia, and historic preservation, it has similar

functionalities to a video game, where the player can traverse, explore and interact with the environment. Hence, game design practices that are intended to improve user experience and intuitive controls, layouts are beneficial to the applications appeal and ease of use.
Application design consists of creating the mappings for input controls, movement options, user interaction with software features and other user experience behaviors of the application.

3.3.2.1. Exhibit display

Since the VR headset is meant to be played standing upright, exhibits are ideally displayed at chest level, so using a display pedestal to provide appropriate height to artifacts fits with the museum aesthetic as well as ensuring the user's comfort while viewing artefacts.
Further improvements adding textures and colors will be made later in the development process, adding further realism.

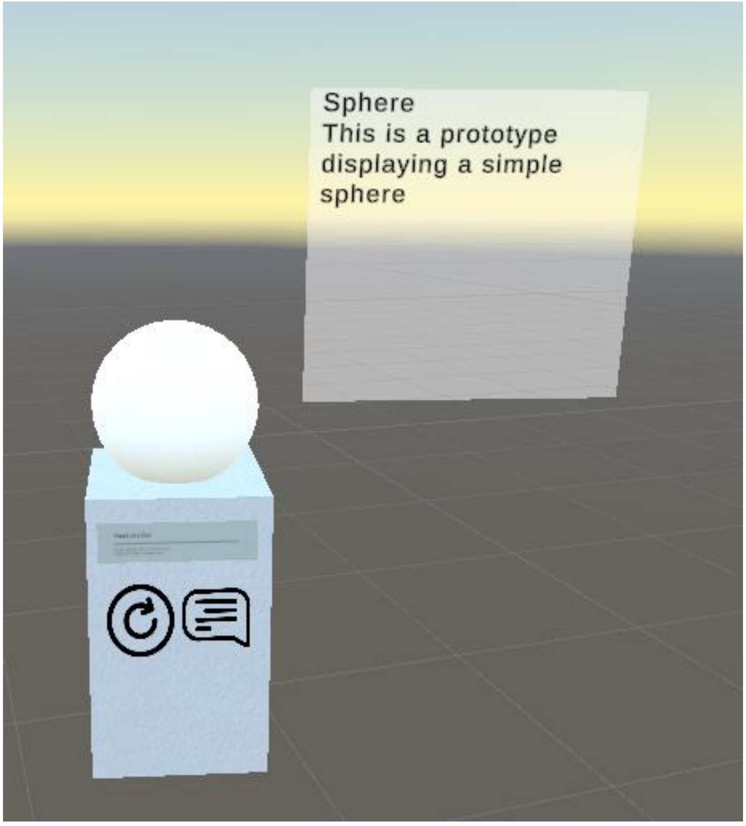


Figure 17. Pedestal concept. The sphere is a placeholder for displayed artifact.

In addition to the pedestal, the exhibit display will also be equipped with various UI elements to take advantage of the virtual nature of the environment. The two buttons visible on the pedestal are the reset position button and the toggle information display button. The plan and functionality for object manipulation by interaction through the use of VR controllers means that the displayed object could be moved, rotated, scaled up and down dynamically or even thrown, so the purpose of the reset position buttons allows for users to simply revert all the changes made to the objects through interaction and restore the object to the initial state on the pedestal. Having a information panel on the object is important for a display to show historical information, details on excavation, object age, etc. The toggle information display will turn on and off this text panel to only show the information if the user chooses and turns off to restore the streamlined and realistic environment of the museum which takes full advantage of virtual reality benefits while maintaining appropriate realism.

To enhance the realism of the Virtual Reality Museum, some features of the real Museum of Ho Chi Minh city is replicated and integrated into the application. One feature is the exhibit pedestal of certain cultural and worship statues, which is then re-constructed in Virtual Reality:

Figure 18. The original display pedestal in HCM Museum (left) and the replica room in VR (right)

3.3.2.2. Exhibit interaction

Offering interactions is one of the key features Virtual reality museums have over traditional museums, establishing a smooth and intuitive interaction system is an important factor in the user flow and the quality of the application.

Using the Oculus Quest 2 controllers as an input interface, user hands will be simulated inside the environment, with accurate finger movements to pick up objects. Interactable such as buttons to enable and disable text descriptions, to reset the objects placement is also in implementation plans, since displayed artifacts in the virtual reality space can be moved around. Supported movements of the artifacts include:

- Physics movements: such as gravity, thrown, collide with other objects.
- Hand movements: rotation, positional movement.

The above movement types simulate a realistic interaction system, similar to how one would interact with real world objects, close inspections from all angles normally obscured would be achievable in this framework.

The object interaction system in pseudocode:

```
Interaction Loop:
        if input from rightThumbstick:
            rotation = ConvertInputToRotationAngle(input)
            rotation = rotation * rotationSpeedMultiplier
            interactingObject.rotation += rotation

            movement = ConvertInputToMovement(input)
            movement = movement * movementSpeedMultiplier
```

```
interactingObject.position += movement
if interactingObject.IsBeingScaled:
        scaleLoop (explained further in section 3.4.3)
```

Figure 19. Pseudocode for interaction loop

```
ScaleLoop:
    If controlPhase == startPhase:
        initialScale = object.Scale
        initialDistance = Distance(leftController, rightController)
    else:
        newDistance = Distance(leftController, rightController)
        scaleMultiplier = initialDistance / newDistance
        object.Scale = initialDistance * scaleMultiplier
```

Figure 20. Pseudocode for scale loop

The interaction loop executes every frame of the application, there are many other calculations being made under the hood of the pseudocode, such as multiplying transform matrices, matching the controller transform with the object transform, creating attachment points, verifying physics system, checking conditions, and so on, the scale multiplier is calculated using the distance between the controller, to simulate the action of grabbing 2 points of the object, moving the controller apart will expand or shrink the object accordingly.

3.3.2.3. Movement

As touched on in the use case section, the primary movement type would be continuous movements, allowing the user to simulate "walking" through the museum environment realistically, being able to see and interact with the displays while doing so. Teleporting was also considered, but this movement method is not realistic, and also not offering fine and smooth movements, the snappy nature of the movement and the requirement to aim the teleport position could cause issues where users want to travel to an exact position, smooth and continuous movement fits this purpose better. Users can also traverse the environment by walking around in the real world since the Quest 2 is equipped with spatial tracking technology, however this is advised against since the boundaries of the virtual environment won't match with the real world, so walking around in the VR world would result in collisions of the player and obstacles in the real world.

User movements will be divided into 2 separate components, both controlled by one controller: Rotation and Position. With these 2 locomotion components, realistic movement can be emulated, the left controller thumb stick Y axis (forward and backwards) controls the character movement in the virtual world and the thumb stick X axis (left and right) controls the character rotation in the Y axis (facing direction) in the world.

The underlying movement system will concurrently execute these 2 movement loops, expressed in pseudocode:

```
Movement loop:
    if input from leftThumbstick:
        rotation = input.RotationInput
```

```
movement = input.MovementInput
ApplyRotation(rotation)
ApplyMovement(movement)
```

Figure 21. Pseudocode for movement loop

Again, the pseudocode is heavily abstracted, the processing of information under the hood is complex: applying transforms, converting input to rotation and movement units, verifying conditions, ...

Movement and Interaction is the 2 key system to interaction with the VR museum space, the plan is to incorporate these 2 systems seamlessly and make the experience as fluid and intuitive for users as possible.

3.3.2.4. Text to speech integration:

A major feature to increase accessibility and offers an alternative mode of engagement for individuals who have difficulty reading or accessing the text content. Additionally, the speech feature enhances the overall user experience of the application. It provides a more immersive and interactive experience for users, as they can engage with the artifacts through both visual and auditory means. This can lead to a deeper understanding and appreciation of the historical significance of the artifacts. The speech feature can also facilitate learning and knowledge retention. By including an audio component, the AR and VR applications offer a multi-modal approach to learning that can benefit users of all ages and backgrounds.
The reading engine used to convert text content into audio formats would be difficult to implement and increase the size of the build file unnecessarily, an alternative solution was utilized: To send a request to a cloud service – Meta Speech Service, and receive the audio files through the internet, letting the cloud API handle the processing, and the endpoint is the application to play the audio file. The process of converting text to speech and playing the audio is as follows:
Raw text (object description and historical information) is entered into the Unity Scene. The text will be sent to a cloud server which processes the text and convert it into a pre-defined voice, we can set the settings for the voice in Unity, configuring the speed, pitch, speaker gender, … The resulting audio file is then cached in the build file, and finally played in the application.
This feature will be implemented in both the AR and VR applications, providing several benefits, including increased accessibility, enhanced user experience, and improved learning outcomes. It is a valuable addition to the application, and it further highlights the potential of technology to create innovative and inclusive educational experiences.

3.3.2.5. AR Application

The blueprint for the Augmented Reality application to be deployed on mobile devices to aid in museum tourism will be outlined in this part. Using markers so that mobile cameras can detect in world space, the mobile AR application will display the 3D model of the specified artefact with added functionality such as interaction, audio, text descriptions to provide information and clearer visuals.
The 3D Augmented Reality functionality aspect of the application consists of 2 main features:

- The object follows the marker’s location consistently in the 3D environment.

- The object can be manipulated by user input such as rotation and scale adjustments.

Pseudocode for the AR application loop:

```
ARModelDisplayLoop:
    If detectNewMarkerImage:
        new Object = GetObjectFromImage()
        Object.position = Image.Position
    Else if updateMarkerImage:
        Object.position = Image.NewPostion
```

Figure 22. Pseudocode for displaying AR model loop

```
ARInteractionLoop:
    If userInput.type == Rotate:

        rotation = ConvertInputToRotationAngle(input)
        rotation = rotation * rotationSpeedMultiplier
        interactingObject.rotation += rotation

    Else if userInput.type == Scale:
        Distance = Distance(leftController, rightController)
        scaleMultiplier = initialDistance / newDistance
        object.Scale = initialDistance * scaleMultiplier
```

Figure 23. Pseudocode for interaction with AR model loop

3.3.2.6. Prototype plan

Before building the application, prototypes will be made to quickly test and implement standalone features before incorporating them together into the full feature set of the software. Having a prototyping step in the development cycle helps to test out feature design and flow, adjustments to existing plans can be made in this step instead of later on in the life cycle which could introduce difficulties and rewrite a lot of code. In addition, having a barebones version of the product allows for testing to observe the intuitiveness and forecast user expectations for the software, as well as keeping track of the application progress.

The simple prototype feature list that needs to be prototyped includes the main features (smaller features can be added later on, prototyping only needs the barebones core features).

+ Virtual reality integration
+ Movement system
+ Interaction system
+ Object display
+ Museum environment

3.4. Prototyping Phase

3.4.1. Virtual Reality Integration

As the Unity3D toolkit by default does not support development and testing with Virtual Reality out of the box, some additional packages and modifications can be added to allow the usage of some development SDK created by Unity for virtual reality development.
The installation of these packages and frameworks are available in the Unity documentation manual [30]. This project uses the latest available version of these packages at the time.

- The unity XR Plug-in framework:

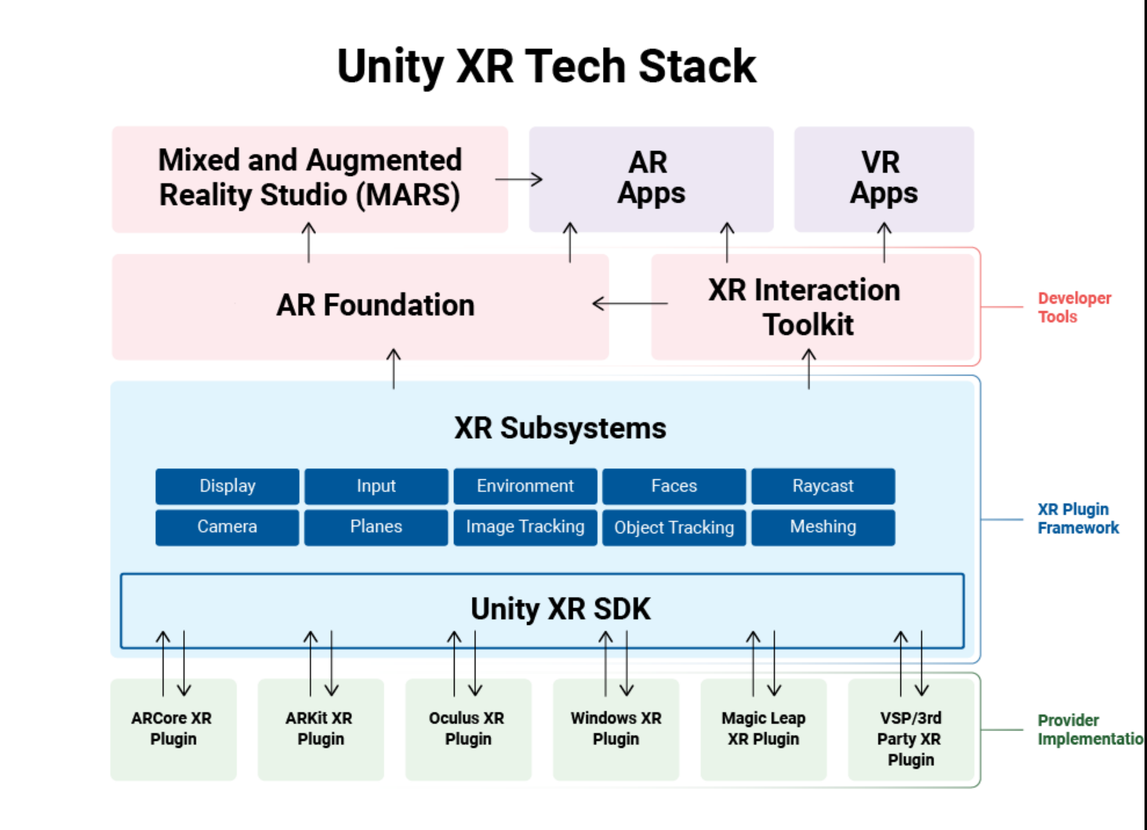


Figure 24. The Unity XR Tech Stack

Unity XR Tech Stack [28], a framework that enables direct integrations for multiple platforms. The tech stack consists of an API that exposes common functionality across the platforms Unity supports and enables XR (VR and AR) hardware and software providers to develop their own Unity plug-ins.
Unity has developed a new plug-in framework called XR SDK that enables XR providers to integrate with the Unity engine and make full use of its features. This plug-in-based approach improves Unity's ability to make quick bug fixes, distribute SDK updates from platform partners, and to support new XR devices and runtimes without having to modify the core engine. The unity XR tech stack allows for development for Virtual Reality platforms, one benefit of the XR tech stack is that it abstracts the underlying architecture and add compatibility of many different headset SDKs, so the final application can be executed not only on the Oculus platform but many other VR hardware (steamVR, HoloLens, PlaystationVR, ect…) [29].
Upon this framework the application will be built, using C# code and another development toolkit called XR Interaction Toolkit to create and implement more advanced features.

- XR Interaction Toolkit:

The XR Interaction Toolkit package is a high-level, component-based, interaction system for creating VR and AR experiences. It provides a framework that makes 3D and UI interactions

available from Unity input events. The core of this system is a set of base Interactor and Interactable components, and an Interaction Manager that ties these two types of components together. It also contains components that you can use for locomotion and drawing visuals.
This toolkit from Unity implements and handles basic VR integration into Unity such as VR camera controls, simple controller inputs like holding objects and basic UI. Furthermore, it provides APIs to lower-level code, allowing modifications and additions to functionality using inheritance or implementing fully customized classes using their interfaces.

3.4.2. Movement System

The plans for the movement system could be implemented thanks to the exposed API from the XR Interaction Toolkit package. Provided with the Locomotion system, it supports both forms of movement available in VR, continuous and teleport. Although some setup is necessary for custom controls, which is not required in this project. Using the right and left thumb sticks, the player avatar moves seamlessly in the museum environment, combined with the headset tracking the direction of the user's look direction, the movement system is intuitive and natural.

3.4.3. Interaction System

In the design phase of the product development plan, it has been outlined that the interaction system must enhance the museum experience and add functionality that the user wouldn't be able to do in traditional real-world exhibitions. This not only includes simple interactions with objects such as picking up, rotating but complex and interesting interactions such as scaling the object bigger or smaller and applying physics interactions with the environment, objects in the environment can collide, thrown, affected by gravity and momentum.
The interactions above would augment and add to the simulation certain realism, furthermore, taking full advantage of the VR technology and the benefits of 3D models.

+ Controller avatar:

For interactions and user controls, there needs to be a representation of the user in the Virtual Reality space of the museum that users can see with the headset. The most important avatar is the controller avatar, the user has to be able to see the locations of the controllers in respect to the virtual environment to be able to interact with objects using the controllers.
To represent the controllers in the virtual space, a specialized hand model was provided by Unity, with finger animations. These finger animations were linked up with the controller by C# code and the XR Interaction Toolkit API, to illustrate finger movements when the user presses buttons on the controllers. The hand models will move in the VR space in accordance with the controller movements in the real world, so the user could see where their hands were, improving user flow experience, ease of use and realism.

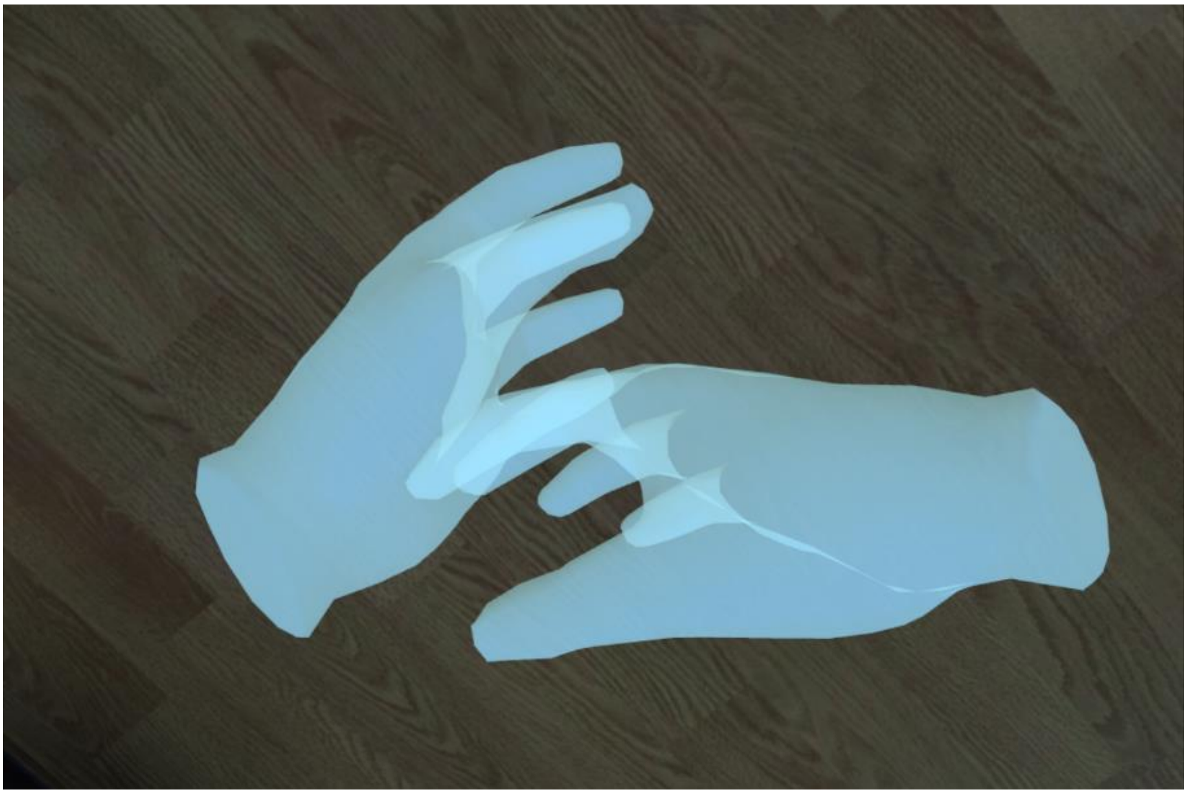


Figure 25. User hand modal react to button presses with finger movements

+ Physics simulation:

The powerful Unity3D engine enables accurate physics simulation such as collisions, gravity, momentum, by adding certain components to the gameObjects in the scene and activating them dynamically by C# scripts.

The costs of physics simulation is relatively high for the platform so this behavior is off by default and is only enabled by the user when it is interacted with. This saves on performance since the system does not need to simulate physics for all objects in the scene.

Using the APIs provided by the XR Interaction Toolkit, the simple picking up objects and enabling physics on artifact models are implemented. The objects while grabbed will follow the controller's position and rotation. With this control scheme, objects can be picked up and rotated using the controllers motion tracking, by moving and rotating the hand holding the controller, the in-simulation hands would also rotate and in turn rotate/move the held artifact, this allows for 360 degrees inspection with closeups of the models.

+ Scaling objects:

This specific interaction is not supported by XRI toolkit, so it has to be implemented by code, by checking for specific inputs and the position of the controllers in space, calculations is carried out and updates the objects size in game. The pseudocode for the sizing interaction:

```
initializeScale:
        originalDistanceBetweenHands = Distance(controller1, controller2)
        objectOrignialScale = objectScale
```

```
scaleLoop:
```

```
        if objectIsHeld and objectIsBeingScaled:
            scaleMultiplier = Distance(controller1, controller2) / originalDistanceBetweenHands
            objectScale = objectOriginalScale * scaleMultiplier
```

Figure 26. Pseudocode for scaling interaction

Museum artifacts can also be scaled dynamically, this feature enables interactions not possible in real life, by holding and pinching the object, its size can be modified by dragging the controllers apart or together, with this system, objects can be enlarged or minimized according to the user.

3.4.4. Object display

Expanding from the display concept in section 3.3.2.1, the final object display prototype is like so:

Figure 27. Using a sample head, the pedestal prototype was built.

Some features of the pedestal include:

+ Reset button:

As the artifact itself is interactable and can be carried to another location or sized differently, the reset button when pressed with the controller will reset the state of the display object, returning it to the original position and correcting the size and orientation.

+ Information panel:

The panel with text behind the pedestal displays the information on the artifact. This text is fully customizable with different font, font sizes, colors, the display panel is also a scroll rectangle which allows users to scroll up and down the text to display long text articles.

+ Information panel button:

This button functions as a toggle for the information panel, switching it on and off.

+ Artefact:

The location of the artifact on the pedestal, this object can be picked up and moved, resized, and rotated using the controllers.

+ Full customizability:

Every aspect of the pedestal can be modified and tweaked appropriate to the model of exhibition, the pedestal can be tall or short, wide or narrow with a few simple edits. The content and formatting of the panel is also customizable, the placement of the object, the location and size of buttons, the customized elements can be saved and pasted using the Unity Prefab system. This allows for the museum architect and designers to fully utilize the power of Virtual Reality to create the display that they envisioned with flexibility.

3.4.5. Museum environment

Before using actual scans of museum buildings, there are some prebuilt museum environments available on the Internet and are imported for use in the project as placeholders.
This environment simulates a realistic museum environment with lighting and displays. With this environment, experiments and tests can be run using the other systems.

Figure 28. Sample Museum building asset to emulate real museum as placeholder.

This leaves features for expanding and enhancing opportunities for the project: scanning or constructing museums based on real world architecture. Implementing such models requires much specialized work including professional 3D scanning and/or 3D modeling.

3.4.6. User Interface

As this application is aimed towards a wide general audience for learning, customization for each user is important. This necessitates a UI, where the user can interact with the game system to tweak the settings.
The settings can range from movement speed, rotate speed and text size. Other settings can also be implemented to allow for maximized customizability such as teleportation points or mini-map.
The panel for UI interaction will be on the left wrist of the user, this way the user can control the orientation with the left wrist and interact with the user interface with the laser pointer on the right hand.
Currently available settings:

+ Movement settings: turn speed and movement speed.
+ Teleport user button: to teleport the user to the starting point of the map.
+ More to be added.

The default UI system for Unity3D does not work to detect inputs for VR, so a custom UI system is created, using the XR interaction system package.

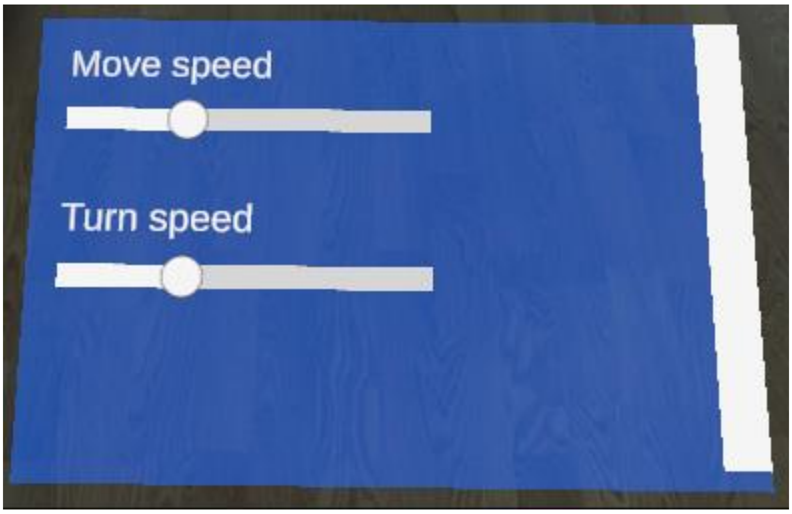


Figure 29. Simple UI prototype

When the button for UI is pressed, the UI attached to the movements of the left controller will appear together with the laser pointer on the right controller. With these interfaces the user can adjust the settings in an intuitive and easy manner. The UI can be disabled toggled off again with the same button or with an X to close button on the corner.
Other UI elements that are expected to be implemented include extra options for convenience such as quick teleportation to a room, adjusting player height or a mini-map.

CHAPTER 4

IMPLEMENT AND RESULTS

4.1. Implementation

4.1.1. Building the application

There are some additional optimization settings available in the export process of the application into .APK format to be executed in Android operating system in the Quest 2. These optimization settings can improve both the performance and size of the final application, as the one of the most important factors in Virtual Reality user experience is the stable and high frame rate to prevent dizziness and discomfort during usage.

Following the official Oculus developer documentation on build settings by Meta[31], there are some basic Unity settings that help you optimize the app performance and quality, and utilize Meta features to ease the app development process.

Some notable build settings:

+ Texture compression: With good texture compression algorithm for assets such as textures and images will reduce package size, decrease memory usage on device, improve graphic processing performance. The optimal choice for the Android operating system is ASTC compression algorithm.
+ Scripting backend: Unity provides support for 2 primary scripting backend to convert C# code into executable code run by the device, Mono and IL2CPP, Mono uses just-in-time (JIT) compilation and compiles code on demand at runtime, whereas IL2CPP uses ahead-of-time (AOT) compilation and compiles the entire application before it is run. The chosen option is IL2CPP provides better support for applications across a wider range of platforms, and it can improve performance across a variety of hardware.
+ XR settings to improve performance: select Color Space option to linear to have realistic rendering, letting colors supplied to shaders within the scene lighten linearly, setting Graphics API to OpenGL ES 3.0, select Multithreaded Rendering to move graphics API calls from the main thread to separate worker thread, and enabling Low Overhead Mode to skip error checking.
+ Quality Settings: these settings will affect how the final application will look on device, having the right balance between graphics and performance is important to a VR experience. Disabling post processing, options such as real time shadows and reflections are kept at a minimum to reduce draw calls and improve frame stability.

After configuring the appropriate settings, the final project is built and exported as a .APK file ready to be installed on Android devices. The final step of installing the application on the Quest is simply choosing the build and run option in the build settings with the quest plugged in via USB-C cable from the development computer.

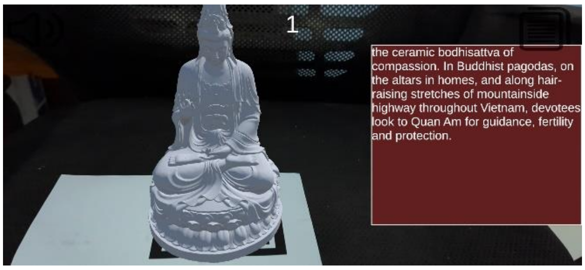
4.2. Product Applications

4.2.1. AR Application:

The AR application is deployed on an Android device (Google Pixel 7 – 8gb Ram) for testing purposes. It utilizes the phone’s camera system, detecting markers and rendering the 3D models in real world space.

For the database of 3D models and artefacts, high quality meshes of historic artefacts such as statues and sculptures with appropriate text descriptions and the voice audio to read them are generated.

The resulting AR application was a success, developing an application that effectively utilizes Unity in combination with 3D technology to display historical artifacts in an interactive and engaging way. The application offers an immersive and educational experience for users, and it has the potential to be used in various settings, such as museums, schools, and cultural institutions.



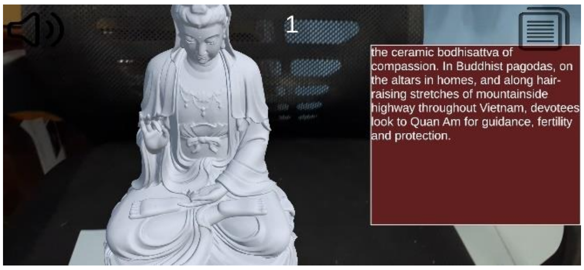


Figure 30. The AR application displaying a white Statue of Quan Am, the picture on the right is scaled up for clearer inspection

The above figure demonstrates the AR application showing the statue and descriptive text, using interactive features, users can rotate or make the object bigger (demonstrated in the right picture) for the best possible user experience.

Figure 31. AR application showing 2 objects simultaneously

The AR application has numerous potential applications in various settings, particularly in museums and educational environments. In museums, the application could be used to enhance visitor experiences by providing interactive and educational information about historical artifacts. Visitors could scan QR codes or use the application to locate artifacts within the museum, and then access detailed information and 3D models of the artifacts through the application. The speech feature of the application could be particularly beneficial in museum settings, as it would enable visitors to engage with the artifacts in a more immersive and accessible way.

In educational environments, the AR application could be used to supplement traditional teaching methods and enhance student learning experiences. Teachers could use the application to provide students with interactive and engaging content that complements classroom lectures and textbook readings. Students could use the application to explore historical artifacts in 3D and listen to audio descriptions, providing a multi-modal approach to learning.

Furthermore, the AR application has potential for future expansion and development. As technology advances and new features become available, the application could be updated and expanded to include additional interactive elements, such as games or quizzes, that further engage users and enhance learning outcomes. The application could also be expanded to include more historical artifacts and information, providing a comprehensive and immersive educational experience for users.

4.2.2. VR Application:

The completed VR application is built and deployed on the Oculus Quest 2 Virtual Reality headset. From the prototyping phase, certain systems have already been built such as movement and interaction. With image processing and 3D construction, a replica room of Ho Chi Minh City Museum is constructed using Unity and implemented in the VR application.

Figure 32. The original room in HCM Museum (left) and the replica room in VR (right)

A successful replica is built with high accuracy and realism, with added advantages of being in a virtual environment where visitors can interact with objects and have extensive functionality.

Figure 33. Close up of the object's exhibition, with interactive elements

This VR application enables people to traverse and interact in a virtual museum, offering a unique and immersive experience for users. This application displays 3D models of historical artifacts, descriptive elements, and audio descriptions that provide a comprehensive educational experience for users. Users could navigate through the virtual museum using a VR headset and interact with the artifacts through controllers and gestures. This would allow users to explore the historical artifacts in a more in-depth and interactive manner and provide a unique and innovative educational experience.

This application not only serves as an tool to preserve and showcase historical artefacts, but it also helps in many other purposes, such as an education tool, an entertainment media, and is also a good foundation for future scientific studies to improve and expand on.

Integrating the 3-dimensional scans of heritage statues for worship, in cooperation with the Ho Chi Minh city Museum. The statues that are displayed in the museum with the topic name "Statues of Worship", are reconstructed and visualized in Virtual Reality:

Figure 34. Full reconstruction of the "Statues of Worship" exhibition from Ho Chi Minh city Museum

4.3. Evaluation

4.3.1. Application size

The final VR project size is 285 Megabytes (mbs). This size taking into account the number of models and textures of artefacts, is very small considering the standard Quest 2 model has 128Gb of storage. This package offers a fully immersive virtual museum environment with interactivity and object descriptions and has potential to be expanded heavily.

The AR deployment build is 43 Megabytes. It is lightweight which is ideal for a wide range of mobile devices, allowing for a wider demographic of users to experience and take advantage of this tool, such as in studies or museum trips.

4.3.2. Application performance

A vital part of a virtual reality application running on the native hardware of the Quest 2 instead of the PC is that the limited resources on the mobile hardware. Furthermore, performance of the application, measured in frames per second (FPS) is one of the most important metrics of user comfort and optimization quality, since low FPS or inconsistent FPS can cause users to be disoriented, dizzy or even headaches. Because of this, optimizing the graphics and algorithms is pivotal to ensuring application quality.

Some performance optimization techniques applied are:

+ Lightmap baking [32]
+ Ensuring high quality but low polygon models, textures, normal maps [33].
+ Minimal physics simulation, only the interacted objects are physics enabled.
+ Ambient occlusion.
+ Lowered image post processing.

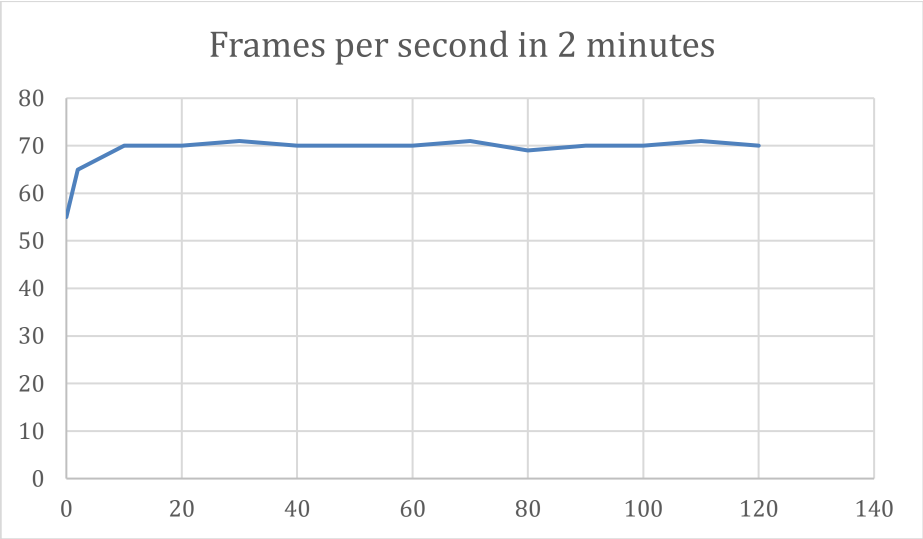


Figure 35. A graph plotting the FPS of the VR application in 120 seconds of operation

Above is the graph for the frames per seconds recording in 120 seconds of runtime in VR. The first few seconds of application start has lower FPS as this is the phase where objects and scripts are being initialized and memory is allocated. After the starting phase the application runs very stably, with a constant 70 frames per second with no stutters or FPS dips while the user moves around the environment and interacts with objects.

Similarly, the performance of the AR application is also optimal, with minimal battery drain and low storage size requirements. The user experience is smooth with no frame drops throughout usage.

4.3.3. Application features

In the implementation process of the outlined application design plan, these functions are successfully implemented with high potential for applicability into many fields, primarily heritage showcase and preservation, introducing the novelty of object interactability in a fully immersive reconstructed museum virtual reality environment.

VR Application:

+ Simulating virtual museum environment in VR, supporting virtual reality headsets.
+ Clean and intuitive UI/UX design.

+ Fully customizable, can modify and edit exhibits, settings, environments with great development potential.
+ Supporting fully dynamic movement.
+ Optimized to run well on VR devices according to benchmarks.
+ Interactability of objects in the scene, including pickup, resize, rotation.
+ Dynamic artifacts showcase with augmentations such as descriptions, auto-rotation.
AR Application:
+ Detecting markers and rendering 3D models in real world space.
+ Clean and intuitive UI/UX.
+ Can be customized, adding new objects to the database, dynamic generation of voice audio.
+ Optimized to run on many devices, Android and iOS is supported.
+ Interaction with models such as rotation and scale.
+ Screen UI to show the description text and reading the audio.

4.3.4. Comparison

Feature comparison between V-Museum application and the VR museum in previous research and some projects on Digital heritage in Vietnam (https://baovatquocgia.baotangso.com/ and https://vr360.com.vn/khu-du-lich-bao-tang)

Application / Feature	V-Museum	Previous research VR museum	Other digital heritage project in Vietnam
VR Platform	Oculus Quest 2 (compatible with other headsets)	Only Oculus Quest 2	Web browser based
Model quality	High quality 3D mesh	3D mesh	Only web 360 images
Environment Audio	Yes	No	No
Tour guide audio	Yes	No	Yes
Interaction	Full interaction/manipulation	No	No
Movement	Continuous	Continuous	Teleport only
Realistic lighting/shadows	Yes	Yes	No
Full view of objects	Yes (dynamic)	Yes (static)	No
Physics simulation	Yes	No	No
Customizability	Yes	No	No
User settings	Yes	No	No
Dynamic description	Yes	No	Yes
UI/UX	Yes	No	Basic

Figure 36. Comparison table between this application and other similar products

4.4. Installation and execution

4.4.1. From .APK file

Installing and running on the Quest 2 or other Android based Virtual Reality headset devices are supported (Quest 2 is recommended because it is the intended device and is tested and

verified on that device). There are multiple ways to deploy an .APK file to the device, this guide will only showcase the method officially endorsed by Meta [34]
Requirements:
+ Meta Developer Account
+ Computer or laptop
+ Meta Quest Developer hub software
+ USB 3.2 to type C
Installing Meta Quest Developer Hub:

- *Download the macOS or Windows installer.*
- *Install the application.*
- *Open the application and log in using developer credentials, which must be the same as used for logging in the headset.*

Connecting the Headset to the Developer Hub:

- *Put on the Meta headset and sign into the developer account you want to use for development.*
- *On the headset, go to Settings > System > Developer, and then turn on the USB Connection Dialog option. Alternatively, you can open the Meta Quest Mobile App, select the headset from the list, and then turn on the Developer Mode option.*
- *Connect the headset to the computer using a USB-C cable and put on the headset again.*
- *Click Allow when prompted to allow access to data.*
- *Connect the headset to the computer using a USB-C cable and wear the headset.*
- *Accept Allow USB Debugging and Always allow from this computer when prompted on the headset.*

Finally deploying the build on the Headset:

- *Locate the APK file on the computer.*
- *On Device Manager, under Apps, drag and drop the APK file in the Add an APK section or click Upload to locate the APK on the computer.*
- *Wear the Meta Quest headset, press the Meta Quest button on the controller to open the menu, click the Apps icon, and from the top-right list, select Unknown Sources.*
- *Open the app from the list.*

4.4.2. From Unity project

Other than the .APK file, for development purposes the original Unity project can be quickly built and deployed on the Quest 2 for testing using Unity's inbuilt deployment system which has integration with the Oculus Quest 2. Because of the support and integration between Unity and Android platform, simple 1-click build and installation method is available:

- *In the Unity Editor with the project open, go into the Build Settings panel.*
- *With the device plugged in the computer, select the desired installation device and press the Build and Run button.*
- *The Unity editor will start building the application and automatically launch the application in the headset.*

Both methods of building is applicable in the installation of the application, however with the Unity project approach the user can also modify the application such ass add/remove/change the exhibits for more customization.

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APPENDIX