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Diplomarbeit

Application of Photogrammetry and Virtual Reality at Building Redevelopment in Existing Contexts

ausgeführt zum Zwecke der Erlangung des akademischen Grades
eines Diplom-Ingenieurs
unter der Leitung

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Abstract

Building redevelopment in existing contexts is a compelling and challenging topic in architectural work. Traditional measurement of the existing contexts done by surveying firms or manual measurement is cost and time intensive. Furthermore, the acquired result processed as extensive overcomplicated 2D documentation contains insufficient visual information about the materiality and architectural details of the existing contexts. Moreover, the design and presentation tools used during the redevelopment process are mostly 2D based and have limited capability to transfer varied types of information and sense of three-dimensionality.

The current workflow of the building redevelopment process could be improved by integrating photogrammetry as a surveying tool and virtual reality (VR) as a design and presentation tool. The aim of this work is to demonstrate how photogrammetry and virtual reality can be integrated into the current workflow as new digital tools, and the areas in which it could help architects during the design and presentation phases.

In the practical part of thesis, different photogrammetry use cases are applied to scan different indoor situations, furnishing and materials to evaluate the feasibility of the photogrammetric survey and VR workflow in real-world building redevelopment processes. Furthermore, based on the scan results, a virtual reality application as the architectural design and presentation method will be developed.

Keywords: Photogrammetry, Virtual Reality, Building Redevelopment.

Kurzfassung

Die Neuentwicklung von Gebäuden im Bestand ist ein spannendes und herausforderndes Thema in der Architekturarbeit. Die traditionelle Bestandaufnahme durch Vermessungsunternehmen bzw. die händische Vermessung ist kosten- und zeitintensiv. Die daraus resultierenden Ergebnisse sind zahlreiche, unübersichtliche 2D-Dokumentationen, die unzureichende visuelle Informationen von Materialität und architektonischen Details über die vorhandenen Kontexte bieten. Darüber hinaus können die 2D-basierten digitalen Entwurfs- und Präsentationswerkzeuge, die während des Neuentwicklungsprozesses verwendet werden, nur begrenzte Informationen und Dreidimensionalität vermitteln.

Der derzeitige Arbeitsablauf des Gebäudesanierungsprozesses könnte durch die Integration der Photogrammetrie als Vermessungsinstrument und der virtuellen Realität (VR) als Entwurfs- und Präsentationswerkzeug verbessert werden. Ziel dieser Arbeit ist es zu zeigen, wie Photogrammetrie und virtuelle Realität als neue digitale Werkzeuge in den aktuellen Arbeitsablauf integriert werden können, und in welchen Bereichen sie Architekten während der Entwurfs- und Präsentationsphase helfen könnten.

Um die Machbarkeit des photogrammetrischen Vermessungs- und VR-Workflows in einem realen Gebäudesanierungsprozess zu bewerten, werden in dem praktischen Teil der Arbeit verschiedene photogrammetrische Strategien für Anwendungsfälle eingesetzt, um Innenräume, Möbel und Materialien zu scannen. Darüber hinaus wird basierend auf den Scan-Ergebnissen eine Virtual-Reality-Anwendung in dieser Arbeit entwickelt, die als Architekturentwurfs- und Präsentationsmethode dienen soll.

Schlüsselwörter: Photogrammetrie, Virtual Reality, Gebäudesanierung.

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CHAPTER 1

Introduction

1.1 Building in existing contexts

Historical building and existing contexts are valuable, visiting historical buildings or existing contexts, every construction, element, and material has a different story to tell, and these reflect the spirits of the time, mentality and identity. The memorable values of historical buildings like the age value, the historical value and the memory value are often unique and irreplaceable. Due to expeditious urban development and high demand for space, architects are often tasked with building redevelopment in existing contexts, which is an interesting, but also a challenging area of architectural work. Architects must evaluate the situation and condition to decide if, or which parts of the existing context should be kept or completely removed. In removing the existing contexts, the risk of losing unsubstitutable values is not invertible. Otherwise, in practice, there are several reasons architects might be obliged to keep the existing contests to the design process:

- Cost factor: Commonly, the scope of the project is small and financial resources are limited therefore architects must downscale additional construction intentions by keeping the existing contexts. Adding architectural interventions could enhance the existing contexts by giving it refreshing new characteristics and purposes (Fig.1).

- Legal protection: To protect the irreplaceable historical, cultural and artistic values of certain historic buildings and monuments, the heritage protection law entered into force (Bacher 1995). This particularly regulates detailed technical issues during the redevelopment process and forces architects to keep specific or entire existing contexts. By doing so, redeveloped historical buildings and monuments can keep their identity and values with a new sense of interpretation and visual appearance. (Fig.2).
- Personal wishes of the customer: Not only public interest but also personal interest plays an important role during the building redevelopment process. Depending on the explicit personal wishes of the customer (e.g. site owner), specific existing contexts, furniture, and materials must be kept after the redevelopment process (Fig.3).

Figure 1. "Reframe": historical vault redevelopment as workshop with minimal architectural interventions, architects: Alexandru Fleseriu + Peter Eszter, Romania, 2016. (@Archdaily)

Figure 2. winning project of the Architizer A+Award: Redevelopment of Matrera Castle in Villamartin. Architect: Carquero Architectura, Spain, 2016. (@Dezeen 2016)

Figure 3. House Rienössl: redevelopment of farm barn as private living house, Due to the personal wishes of the customer, the barn and its construction are kept after the redevelopment. Architect: Wolf Reicht Architects, Austria, 2018 (@DerStandard.at)

Building redevelopment in existing contexts can have extraordinary architectural results, which not only serve the design purpose, but also enhance the existing contexts. However, the building redevelopment process mostly requires additional on-site investigation and detailed planning afterwards. Due to tight schedule plans and to avoid tedious efforts with other planning disciplines (e.g. structural engineers), architects sometimes intentionally prefer to plan and build without existing contexts to reduce costs and simplify the building redevelopment process (Seiferlein 2019). This means the existing context will be torn down entirely (if the law does not prohibit doing so), and only static relevant elements will be kept after this process. Unfortunately, in doing this, numerous interesting architectural details like cornices and reliefs, historical roof constructions, and other relevant and unique materials and elements are also removed. This causes a loss of architectural identity for the building and is not economically sustainable in the long term.

1.2 Building in existing contexts with 3D scans and VR

With continuously changing building norms and the increased complexity of the building redevelopment process, architects have already adapted the digital workflow by using numerous digital tools such as laser scans, computer aided drawing (CAD), and rendering software. The digital workflow of the redevelopment process has particularly improved efficiency, which allows architects to accomplish extraordinary projects with a great precision. Nevertheless, with the upcoming digital tools, specifically with application of photogrammetry and virtual reality, the current workflow of building redevelopment could be further improved by applying photogrammetry as a survey method, thus enabling architects to obtain a detailed survey with extensive information on the site. With integration into a 3D-based virtual reality (VR) platform and using VR as an active platform, architects and other related disciplines could use VR as a design tool to review, edit and present the building, or as a communication and presentation tool for customers (e.g. clients, site owners) in a immersive environment to improve design efficiency. In practice, VR and photogrammetry as new digital tools are already playing a role in day-to-day work in architectural and other related fields. While architects use VR as design and presentation tool, real estate firms use photogrammetry to record sites and represent them with VR (@MediaNetzwerk). However, the mixed usage of both tools in architectural practical work is still rare, although one successful usage of VR and photogrammetry was recorded in spring 2019, when the Bartlett School of Architecture created a VR tour for Lia’an History Museum in China, which was measured using photogrammetry and exhibited as a VR tour in London, while the museum itself was still under construction (Fig.4) (@Dezeen 2019). In other words, exhibition visitors could “walk” inside the museum halfway around the world, which had not yet been finished. This specific example is not related to the building redevelopment process; however, it demonstrates the capability and new upcoming possibilities of VR and photogrammetry as digital tools in the architectural domain, which could thus be integrated into the current building redevelopment workflow.

Figure 4. Top: Lia'an History Museum in China. Bottom left: VR-tour created from photogrammetry. Bottom right: VR-tour at exhibition in London

1.3 Current building redevelopment workflow

The workflow of the building redevelopment process is complex and requires multiple disciplines to accomplish a single project. In practice, the procedure for the redevelopment of each building varies depending on multiple factors and conditions, however, from the perspective of architects, it could be generally described as: preparation, planning and presentation phases. Nowadays, architects and related technical experts already implement different digital tools into different steps to accomplish a fully digital workflow (Fig.5).

Specifically, during the preparation phase, in order to record the building site, architects and customers need to hire professional survey firms to apply laser scans to the existing contexts, which will be further processed as 2D CAD drawings. However, to record the situation and other specific contents, additional digital pictures need to be taken of the site. During the planning phase, architects implement 2D CAD drawings into CAD or any other building information modeling (BIM) software, which allows architects to draw digitally in 2D or 3D based systems (Donath 2008). As the final step, for communication purposes, numerous analog plans from different views and levels are plotted on paper. To give customers a better idea and help them imagine the result, physical built models and photorealistic pictures must additionally be produced using rendering software (Günthner 2011).

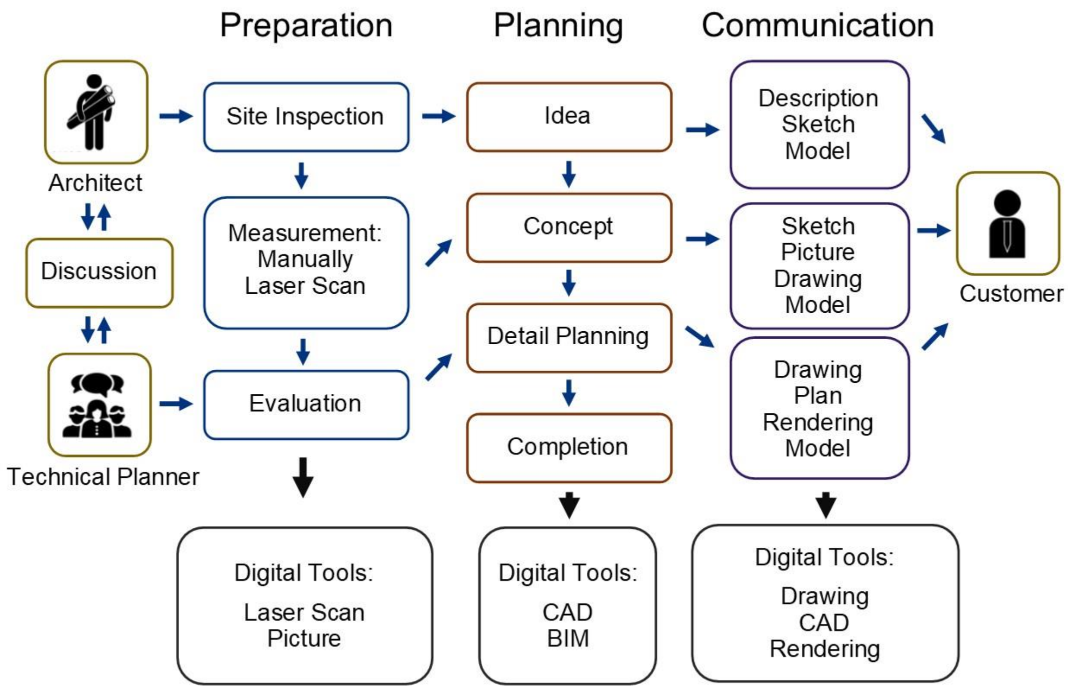


Figure 5. abstracted schematic demonstration of redevelopment process and digital tools applied during each phase.

1.4 Current technical challenges in the redevelopment process

Each existing building is defined by its complexity and uniqueness, thus requiring detailed information about the geometry, material, connection, position and condition as the documentation basis for the further redevelopment process. Therefore, the first step of the preparation phase is building measurement. With commonly applied laser scan technology, survey firms can provide architects with detailed 2D drawings based on the laser scan result. However, often the scope of the redevelopment project is small, and the hiring of professional surveying companies expensive, thus architects and customers still prefer manual measurement. The problem with the practice of manual surveying is firstly inaccurate information gathering due to inaccessibility, inappropriate instruments and unavoidable human errors. The content gathered from manual measurement is often inadequate, specifications such as the materiality and conditions are not included, and complex shapes (such as an interesting cornice or relief) are often strongly abstracted or not measured at all.

Moreover, the current digital workflow is still primarily 2D based, which consists of a tremendous number of documents which are not self-explanatory enough and often cause additional work. Also, during the planning phase, architects do not have the possibility of re-engaging with the site instead of visiting the building site multiple times. Furthermore, these overcomplicated 2D line-based plans regarding elevations, sections, details and views often cause misunderstandings with other technical planners, and in practice it often causes plan errors and additional costs during the redevelopment process (Günthner 2011).
Lastly, using analog plans and pictures as the presentation method for customers (e.g. site owners) is not convenient. Due to the complexity of the redevelopment project, the customer often cannot understand the design and spaces only by reading 2D-based documentation and pictures. As a result, the customer could be dissatisfied with the final redeveloped building, which is an unfavourable outcome for architects.

To summarize, these common challenges are caused by the current digital tools and workflow during the building redevelopment process. However, the integration into current workflow of photogrammetry and virtual reality as digital tools, could improve and simplify the building redevelopment process.

1.5 Integration of Photogrammetry and VR into the architectural workflow

With the rapid development of photogrammetry and virtual reality (VR) systems, other industrial related disciplines have already integrated these technologies to improve the digital workflow. These digital tools also offer architects wide ranging possibilities, specifically, with the integration of photogrammetry as a survey and digitalizing method and virtual reality as a documentation, editing and presentation tool, the current digital workflow of the building redevelopment process could be adapted (Fig.6).

By applying the photogrammetric survey as a reliable measurement technique, not only geometry, but also all other relevant information on existing contexts will be obtained. This new type of realistic digital representation of the site allows architects to investigate the existing contexts more precisely for their further design operations; by using VR as a 3D visual based digital platform, multidisciplinary professionals could discuss and perform architectural changes and represent the redevelopment results in a virtual environment without physical appearance or additional costs. The experience of “standing inside it” of virtual reality stands out compared to traditional 2D based platforms in many aspects.

Since virtual reality is an audio-visual communication platform, customers could understand the design and redevelopment stages step by step and sense a realistic perception of 3D space. This new type of presentation simplifies the communication between architects and the site owner, and could also accelerate the potential purchase decision. Moreover, architects could perform photogrammetry to digitalize architectural elements and materials to enhance the whole workflow.

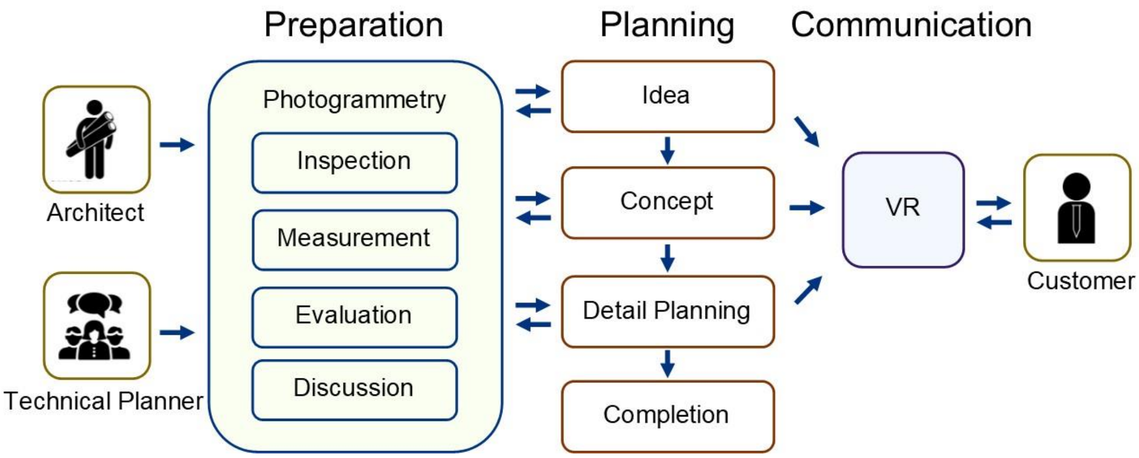


Figure 6. schematic demonstration of adapted version of digital workflow: integration of photogrammetry and VR.

CHAPTER 2

Photogrammetry as an architectural surveying tool

The word “photogrammetry” consists of three syntaxes, “photos” means light, “gramma” means drawing/writing and “metro” means to measure. Therefore, photogrammetry means “measuring by drawn light” (Slama 1980), which already describes the main function of photogrammetry: a survey technique to recreate the geometry of objects by taking pictures. Nowadays, photogrammetry is applied as a survey technique in widely different fields of study and businesses: Remote sensing companies create 3D topography by using satellite images from space, archaeologists survey excavation for research purpose, entertainment companies make digital assets for movies and video games, and the police also use photogrammetry to recreate crime scenes (ASOP 1984).

With better camera devices, increasing computing power and development of photogrammetric reconstruction software, photogrammetry has become popular and can be performed in a cost and time effective way. It is gaining in importance and offers architects new possibilities to apply photogrammetry as a surveying tool.

2.1 Historic overview and definition

Photogrammetry was developed shortly after photography itself was invented in 1830. Even though the interest of photogrammetry in the first place was for military organizations to survey and map new colonies, surprisingly, the first practical application of photogrammetry was by an architect, Albrecht Meydenbauer, who also coined the word “photogrammetry” in later research and applications (Kraus 2007).

In practice, photogrammetry in the architectural domain can be divided into five subareas (Fig.7) depending on the image taking distance (d):

1. Aerial photogrammetry, d ~ 10 – 300 m or above, distance varies depending on level of detail, images are taken from airspace with drone or aircraft.
2. Terrestrial photogrammetry, d ~ varies (shooting position is earth-fixed)
3. Close-range photogrammetry, d < 300 m
4. Super close-range photogrammetry, d < 3 m
5. Micro photogrammetry, d < 1m

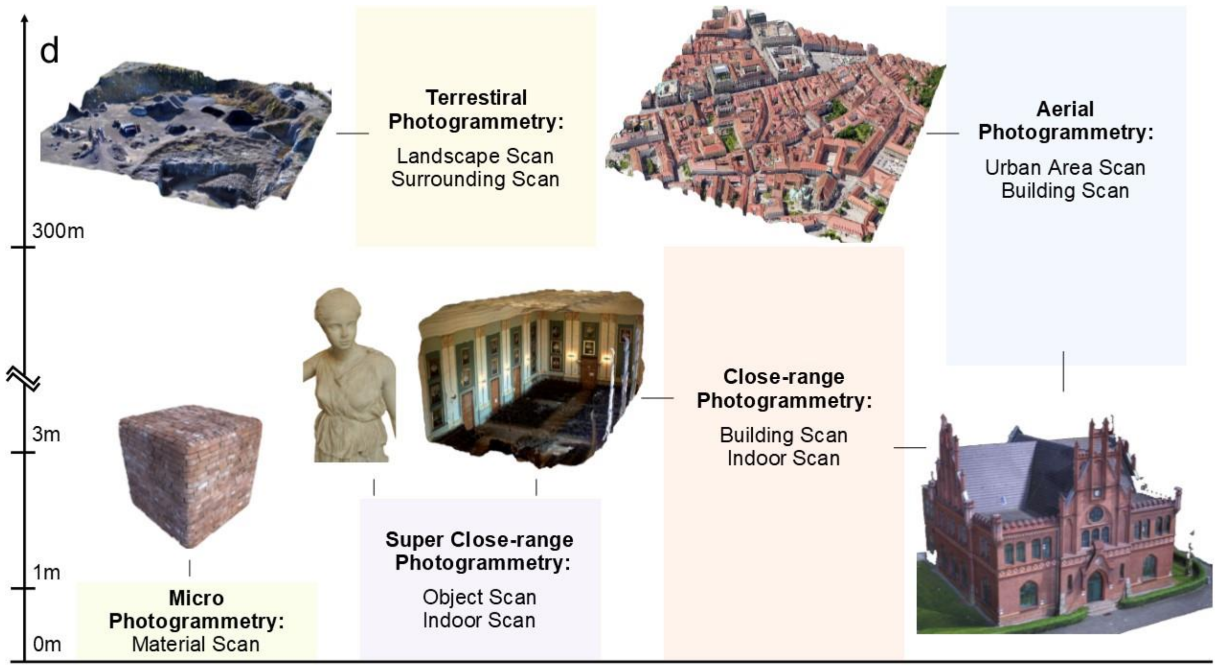


Figure 7. subareas of architectural photogrammetry application

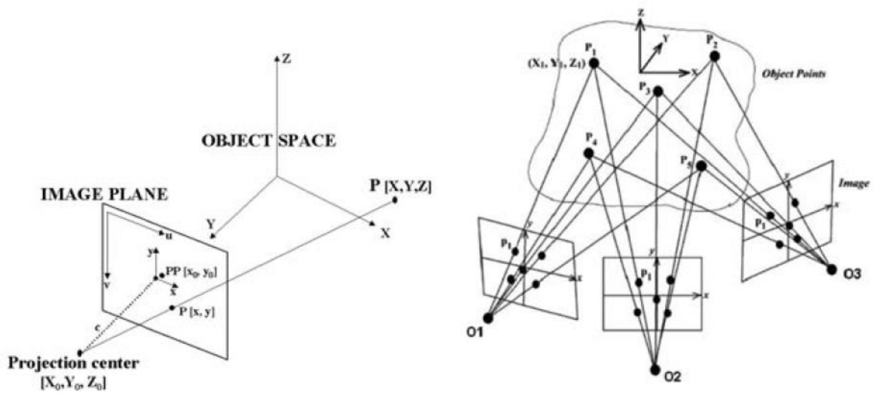
With the capability of photogrammetry, architects and urban planners could apply this technique to record city regions and existing contexts for their specific uses. Despite the wide ranging applications and purposes of photogrammetry, the 5 main characteristics (Heipke 2017) of photogrammetry always remain the same and could be listed as:

1. Contactless survey
2. Short recording time
3. Areal and pictorial documentation
4. Evaluation of two, three or four dimensions
5. Possibility to survey object, independently of the size of the object

2.2 Principles of photogrammetry

The main function of photogrammetry is to survey objects with pictures taken of these objects. This photo measurement technique is achieved with two fundamental mathematical principles (Fig.8):

1. The collinearity principle: the projected geometry of planar images is colinear to its geometry in the 3D object space, which means the coordinates of projected geometry on image plane could be calculated with given factors (e.g. vector algebra, linear algebra) (Slama1980).
2. Bundle principle: by using multiple planar images of projected geometry to further align these images to the corresponding positions, the corresponding representative points of geometry could be reconstructed with bundle triangulation in a non-physical 3D space.



(a) Collinearity principle (b) Bundle principle

Figure 8. fundamental principles of photogrammetry, source: http://what-when-how.com/wp-content/uploads/2012/06/tmp874583.png

In practice. besides the scale of objects and camera devices, the images taken with numerous points on each of the images could be detected and selected, and based on the bundle triangulation, the corresponding position of these images could be defined and furthermore the geometry of scanned objects could also be determined.

2.3 Application of architectural photogrammetry

2.3.1 Documentation of architecture and existing contexts

The first and most widespread application of architectural photogrammetry was for building documentation. Shortly after photogrammetry was invented, Meydenbauer applied this new technique to survey and document architectural monuments by taking pictures with his self-invented receiving chamber. In 1885, the world's first photogrammetric institute for photogrammetric documentation was established in Berlin due to his work.

Between 1885 and 1920, he and his institution successfully documented over 2,600 objects in about 20,000 images. Based on those photogrammetric documentations, the French Cathedral in Berlin, which was critically damaged during World War II, was reconstructed between 1977 and 1982 (Albertz 2001). This could be considered as the first successful usage of photogrammetric documentation (Fig.9).

Figure 9. French Cathedral in Berlin: on the left: photogrammetric documentation of cathedral from Meydenbauer. on the right: reconstruction

Nowadays, with modern camera devices and simplified digital workflows, applying photogrammetry could survey historical buildings in an inexpensive, non-destructive digital way in a short period of time. As result, different outputs can be obtained after the reconstruction process (Fig.10):

- Obtaining 3D geometry to review and investigate the condition with the photorealistic textured model.
- Generate rectified views (e.g. façade of buildings) as architectural documentation.
- Plot multiple (vectorized) plans with additional software.

Architects and other related disciplines use these outputs for various different usages to maximize the potential of the architectural photogrammetry application.

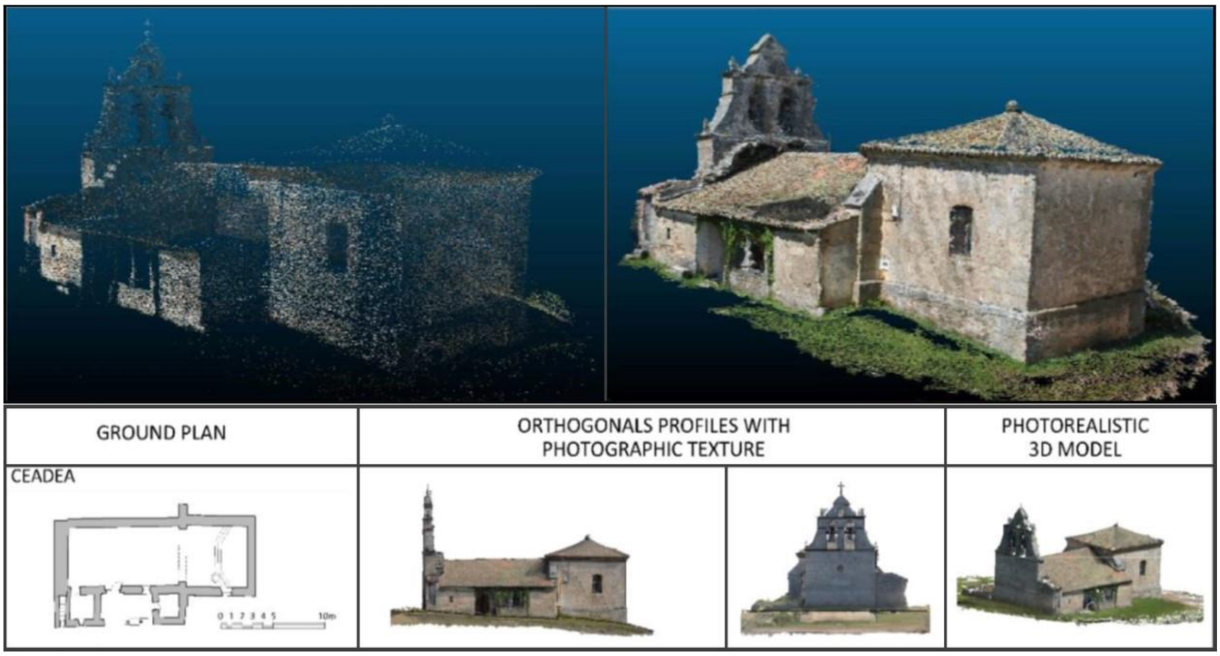


Figure 10. photogrammetric scan and outputs of the church of Ceadea. (Gago 2014)

2.3.2 Photogrammetry as an analytic tool

Often historical buildings are strongly deformed and eroded by nature, and their complex original geometry and structure become even more irregular and extremely intricate. With the application of photogrammetry, the structural engineer and architects not only use the aforementioned outputs as passive results but also actively use the results as an analytical tool for a prevention and restoration basis. After implementing the photogrammetric records as a 3D analytical model, several types of analysis such as metric, geometric, construction and structural analyses (Fig.11) could be performed to spot the weak point of a building to avoid potential planning errors (Cámara 2001).

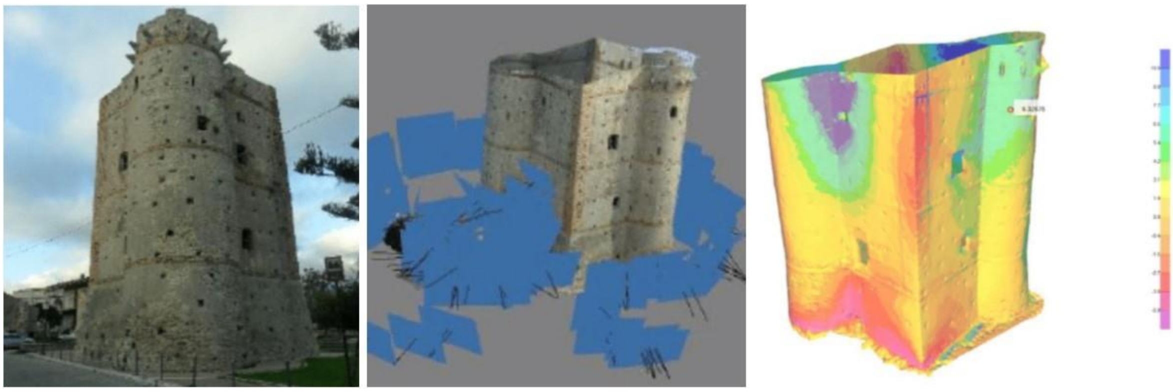


Figure 11. structural analysis of one masonry castle in Italy, performed with the application of photogrammetry. from left to right: 1. on-site photogrammetry image 2. photogrammetric result 3. seismic structure analyses based on photogrammetry result (Barrile 2015)

2.3.3 Applying photogrammetry as an architectural visualization and representation tool

Since most photogrammetry reconstruction software has the possibility to export the results in digital formats, the results could be further exported into other digital applications as a new method of visual communication, which makes photogrammetry itself not only a documentation tool, but much more like a visual representation tool. By integrating the photogrammetry scan into computer aided drawing software (CAD), architects could represent the 3D model on monitors to show important information on the scanned existing contexts. Furthermore, with better mobile device capability and internet accessibility, the scan results could be uploaded online and reviewed with an internet browser as the real estate presentation method (Fig.12). The realistic, textured model of the building allows users to review the textured 3D model and floorplans from computer or mobile devices worldwide. Instead of using numerous 2D plans and pictures, this method improves and simplifies utility, especially for non-professional users (e.g. customer, potential buyer).

Figure 12. online scan review with an internet browser as real estate presentation: on the left: the 3D overview of a house in Pennsylvania. on the right: textured floorplan of the house. (@Matterport)

By going a step further, switching from the traditional presentation medium (monitor) to VR systems (Bähr/Vögtle 2005), users could explore inside the scanned building in a truly immersive 3D environment (Fig.13). This method enables not only the possibility for a better functional and technical understanding of the context, but also the user's own presence and the sense of space in the artificial environment.

Using VR as a visually based presentation method with high visual information content offers professionals and non-professionals several new possibilities for different use cases.

Figure 13. photogrammetry scan in VR, accomplished by company REALITIES: on the left: VR user with HTC Vive. on the right: Photogrammetric scan of existing contexts inside of VR. (@Lang)

2.4 The digital photogrammetric workflow

Today, with digital image acquisition and sophisticated photogrammetry reconstruction software, the photogrammetric workflow has become highly digitalized and convenient. Beside the wide ranging applications and reconstruction software used, the digital workflow of photogrammetry is consistent and straightforward. It could be divided into data acquisition, reconstruction and post processing phases. (Fig.14)

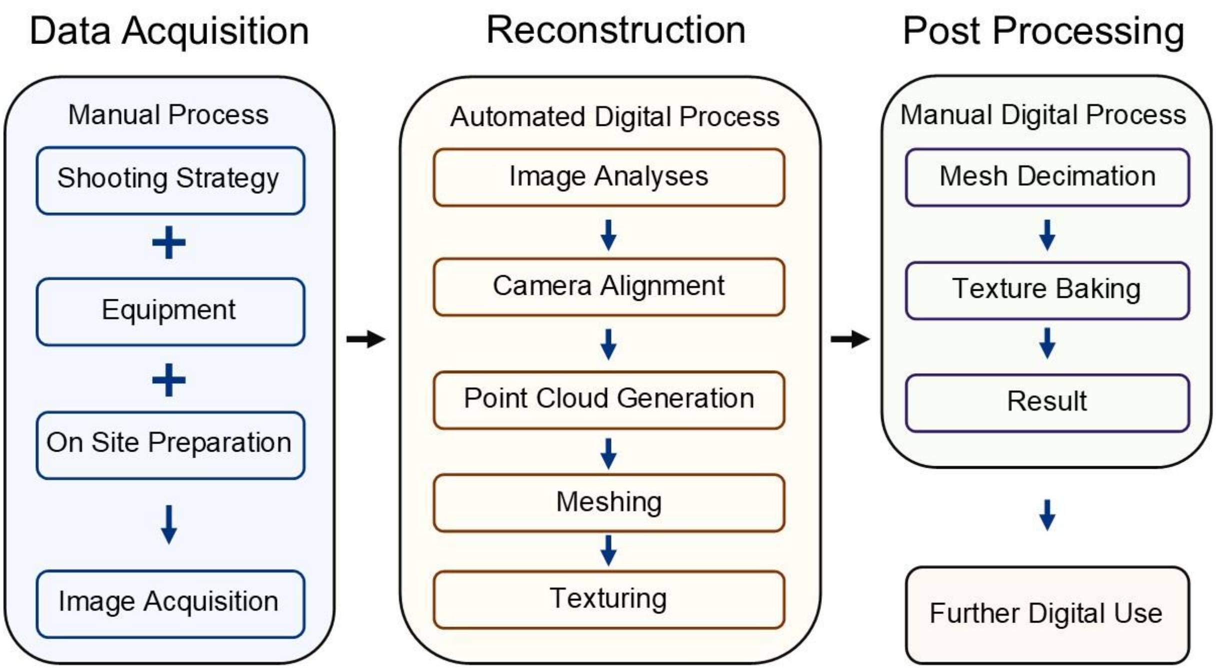


Figure 14. schematic demonstration of photogrammetric workflow

To understand photogrammetry in real-world scenarios and its workflow, it is necessary to understand each step of the photogrammetric workflow and the fundamental technical background of each step.

2.5 Data acquisition

Each photogrammetric workflow starts with the data acquisition phase. The goal of this phase is to take reliable pictures of the site for the further reconstruction process and it is the most essential part of the work. Therefore, the right picture shooting strategy and capable equipment must be chosen from the beginning. Moreover, it is also important to understand how light and the surface condition of the building could affect images, in order to setup the appropriate shooting conditions on site. Therefore, these three important aspects of the data acquisition process will be introduced.

2.5.1 Shooting scenarios and strategies

Depending on object size, object geometry, shooting distance, and accuracy, photogrammetry is practiced with broadly different equipment using various shooting strategies. Considering the relationship between the position of the operator (photogrammetrist) and the object, there are two types of shooting scenarios: interior and exterior photogrammetry (Fig.15). It is also worth mentioning that “exterior” and “interior” are determined by the scanned object, not by the shooting location, for example: surveying a chair inside a building is, per se still an exterior photogrammetric process.

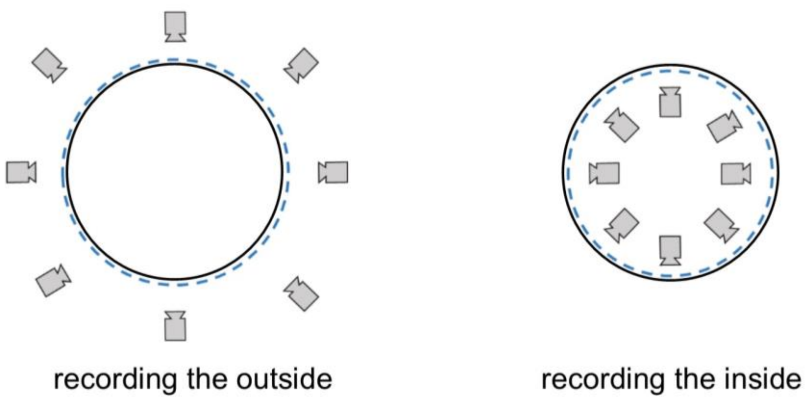


Figure 15.on the left: exterior photogrammetry, on the right: interior photogrammetry

Furthermore, so long as images can be gathered from the objects, there is no limitation to the scale of scanned objects. Specifically, depending on the desired result, application of architectural photogrammetry can be performed as exterior photogrammetry to record the building from the outer side, record objects from smaller distances, and scan surfaces to produce digital materials. To record indoor rooms, interior photogrammetry could by applied from the inner side. To achieve the best result, it is essential to set up the correct shooting strategy from the beginning.

Whether it is interior or exterior photogrammetry application, the fundamental rule stays the same: take continuously overlapping pictures with at least 60% (better >80%) overlapping area (Fig.16).

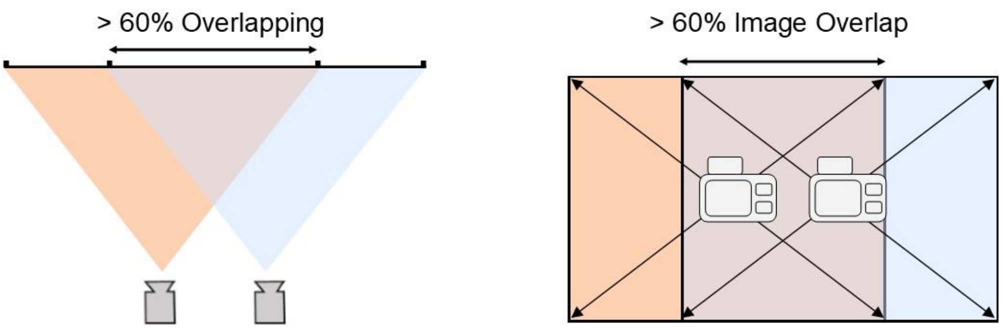


Figure 16. rule to take loop of images: at least 60% image overlap

2.5.1.1 Exterior architectural photogrammetry

Building Scan

By applying close range photogrammetry, existing contexts (e.g. buildings, sites) could be collected. In practice, image acquisition could be achieved with handheld digital cameras or with the help of a camera-drone (or a combination of both devices). Depending on the physical condition of the building and its accessibility, three different shooting strategies (Gago 2014) could be used to obtain different results:

- Circular network: The essential idea is to take pictures around the building several times, each time with different angles and camera heights.
- Planar or mosaic network: to record the façade of the building. This can be achieved by moving the camera parallel to the façade surface, which is the fastest method.
- Independent basic network: primarily used to record a small part of the façade or an isolated part of architectural elements. It is a useful method to obtain details of a façade, such as a cornice and relief. (Fig.17)

Figure 17. different methods (from left to right): circular network, planar or mosaic network and independent basic network.

Object Scan

Similar to the building scan strategies, the aforementioned strategies could also be applied to survey a smaller object, like a statue or specific piece of furniture. However, since smaller objects are more practical and could possibly be removed from the site, another method: the so-called “turntable” - could be applied (Fig.18). By putting the scan object onto a rotatable surface, continuous loops of images can be acquired from fixed camera positions.

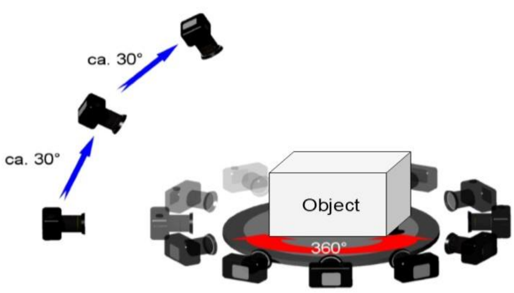


Figure 18. turntable method

Material Scan

During the redevelopment process, based on the wishes of customers or for other reasons, specific existing materials (e.g. flooring, textile) should be kept and applied in the redevelopment project. Since the materials in existing contexts are often specific and unique, digital versions of them cannot be obtained. Therefore, it is helpful and necessary for architects to create their own digital material to study the design with the specific material applied. Moreover, architects could use this material for digital architectural presentations and visualization.

In the field of computer graphics, materials are understood as one set of surface textures, which not only contain the visual colour information, but also physical properties like reflection property and geometric surface behaviours. With different materials applied to corresponding geometry, a realistic appearance could be accomplished (Fig.19).

Figure 19. Rendering of building with different materials applied in render software V-Ray

With the application of micro photogrammetry, it is possible to scan physical material surfaces and to publish it as a digital material by using material authoring software. Generally speaking, to create a realistic digital material which simulates its surface properties physically, additional texture maps are needed to provide additional surface information. Each of these texture maps contains certain information to describe specific physical properties and behaviours of the material, so by combining texture maps together, a digital "material" could be created. Therefore, a reliable digital material should contain (at least) the following texture maps (Fig.20) (Seifert 2015):

- Albedo: Base colour information, determines the chromatic appearance of the material.
- Normal map: determines directions (vector) of surface-normal with the chromaticity (R-B-G code instead of X,Y,Z vectors), which describes the physical structure of the surface of the material (Fig.21).
- Ambient occlusion: A grayscale-based texture map, it determines in which area indirect light has less impact on the material, to simulate a more realistic pronounced detail of shadows.
- Height map: A grayscale-based texture map, which describes the relief of the material (Fig.22).
- Roughness: Describes whether the material is smooth/rough or not, to determine the sharpness of reflection.
- Specular: This map states in which areas reflection should appear or not.

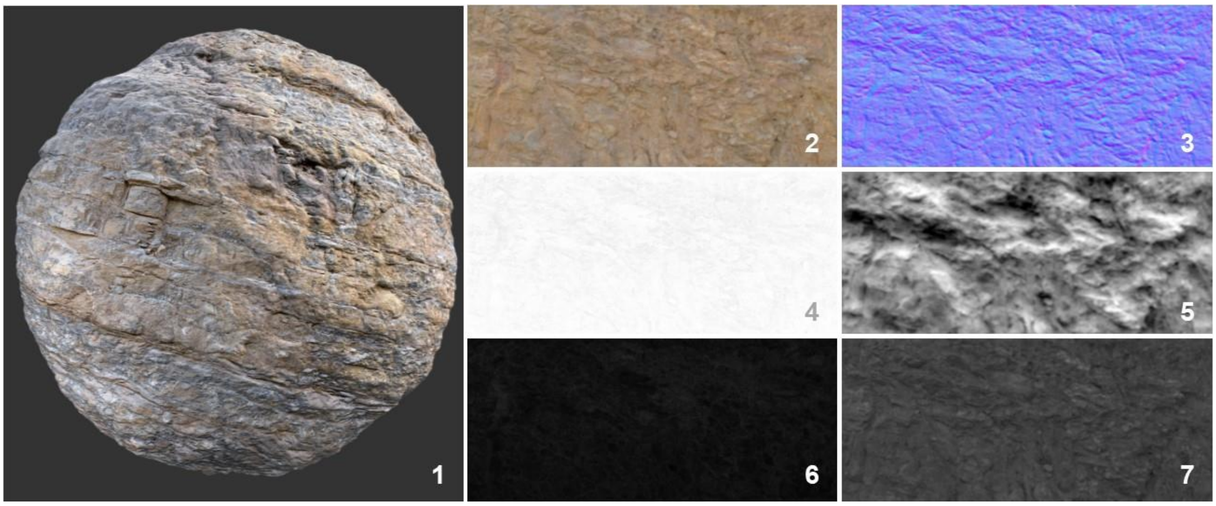


Figure 20. 1. the digital material 2. albedo map 3. normal map 4. ambient occlusion 5. height map 6. roughness map 7. Specular

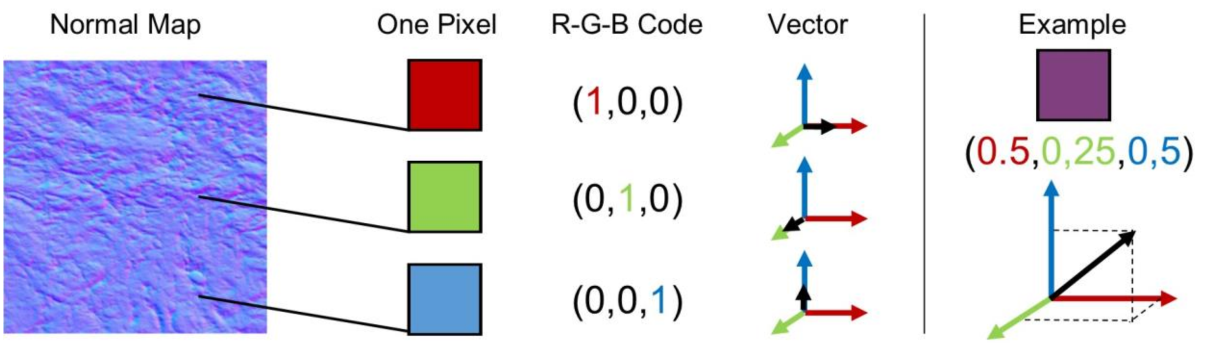


Figure 21. normal map

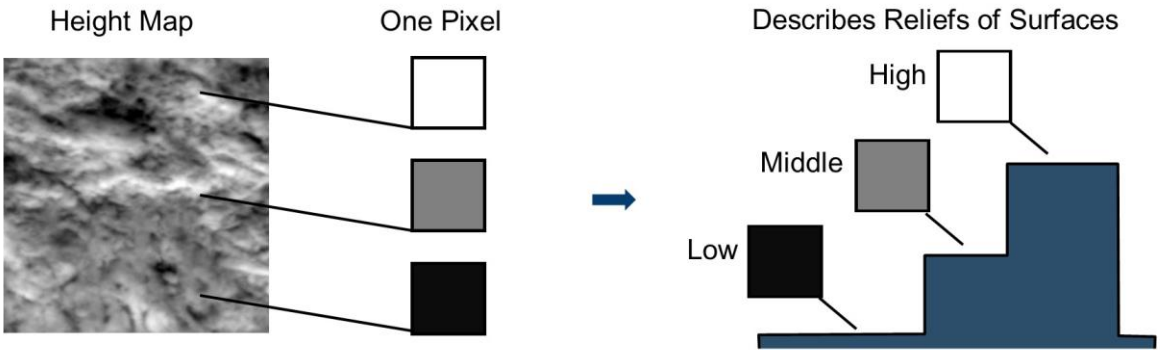


Figure 22. height map

Material authoring software with an integrated photogrammetric pipeline allows users to scan physical material with images taken in certain lighting conditions (Fig.23). The image acquisition technique is to illuminate the scanned material with ~20 degrees altitude to gather separate images from 8 different illumination angles (45-degree offset) from a fixed point above the material. Additionally, one extra image is taken above the scanned material with diffused light to generate base colour. By setting up the right shooting scenario, these images can be gathered and processed as digital material (Fig.24).

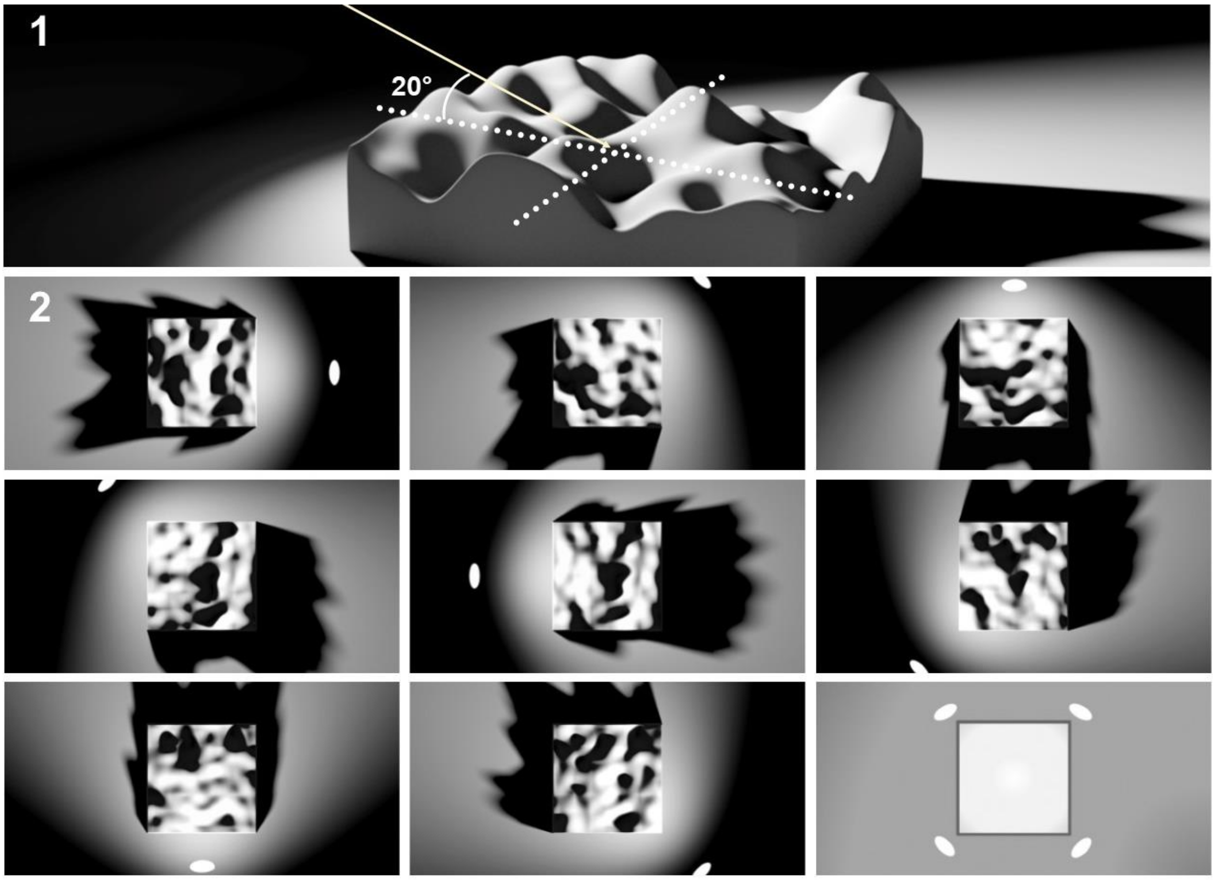


Figure 23. the photogrammetric principle of material scan: 1. lighting angle 2. shooting of multi-angle images and one image above the material with diffused light

Figure 24. micro photogrammetry: shooting strategy and digital material gathered

2.5.1.2 Interior architectural photogrammetry

To achieve the best result when applying interior photogrammetry, it is necessary to adapt the shooting method based on the physical condition of the existing contexts. Due to the physical boundaries of interior environments (walls, narrow spaces), specific camera moving patterns should be planned. Based on different use case reports (@ Pix4D) and studies, the best way is to position the camera direction perpendicular to the wall and move the camera parallel to the wall surface to take a loop of images (Fig.25). Additionally, to obtain a reliable result, multiple loops of pictures should be taken. Meanwhile, the camera height and the camera direction should be adjusted by each loop differently (Fig.26). Since interior photogrammetry is performed in an enclosed environment, additional light sources are often essential to ensure image quality. Certainly, in practice, based on physical conditions of the existing contexts, it is unavoidable but applicable to deviate from this rule slightly, however, images with at least 60% overlapping areas must be guaranteed.

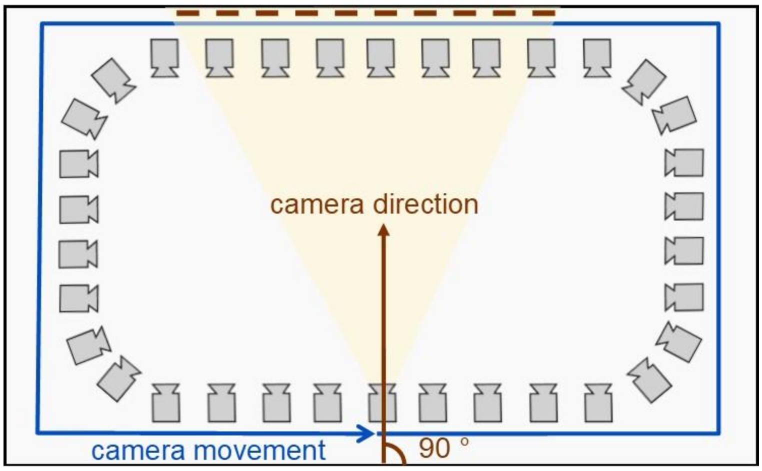


Figure 25. schematic top view of taking loop of pictures inside of a building

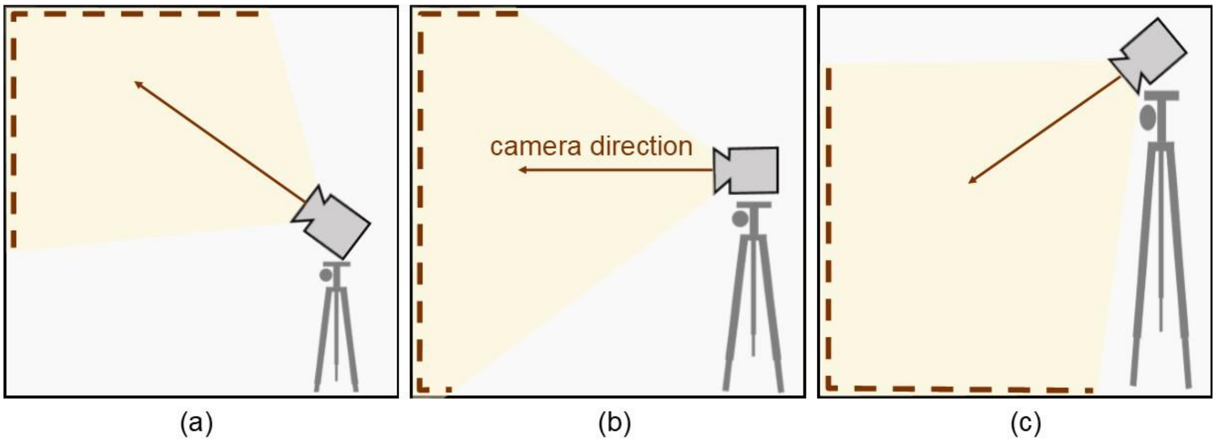


Figure 26. schematic side view of camera adjustment by each loop. a). camera height is low, camera direction pointing to ceiling b). camera height is normal, camera direction is parallel to the ground c). camera height is high, camera direction is pointing to the ground

2.5.2 Equipment

Development of photogrammetry is closely related to the development of camera devices. Better camera devices are capable of capturing and producing pictures with better image quality, which enhances the quality of the result of photogrammetric scan results.

The first analogue photogrammetry image-taking device was invented by Meydenbauer in 1890. He used glass as the emulsion carrier, which only had a 40cmx40cm format. Since 1975, when the first digital camera was created by Kodak, and with the outstanding advantages in digital cameras, digital cameras have increasingly been preferred over analogous ones in the field of photogrammetry application (Maître 2017).

Nowadays, digital cameras can easily achieve a resolution above 4000x4000 pixels by directly transmitting and saving signals in a digital format. With continuously falling prices and better quality of digital camera devices, these have become the most used consumer-friendly photogrammetry tools (Luhmann 2010). Depending on whether the application of photogrammetry is aerial or terrestrial, recording distance, accuracy, and result usage, widely different types of digital cameras are used for photogrammetry.

To apply aerial photogrammetry, a drone with a camera attached is the commonly used tool. This can take loops of pictures in airspace with a handheld controller in a cost and time effective way (Fig.27). Photogrammetry with a drone is especially useful if the scan location cannot be accessed by a person physically.

Figure 27. drone, model Mavic Phantom 4 Pro v2.0 with handheld controller: with 20-megapixel camera attached

For terrestrial and other types of close-range photogrammetry, handheld digital camera devices are the preferred tools.

The most common consumer-level handheld digital cameras come in two forms: digital single-lens reflex cameras (DSLR) and the smaller digital camera modules implanted into smart devices (e.g. the digital camera module attached to smartphones). Despite the size and mechanism of DSLR cameras and smartphone cameras, the fundamental technical principle of image capturing is identical; by recording the light which is collected from the lens, the sensor digitalizes the signal and saves it in digital format.

However, three factors make DSLR cameras outperform smartphone cameras (Fig.28). These are:

- Lens: Modifiable lenses give a DSLR camera the ability to zoom in and out without any loss. A smart device camera module has only one small, fixed size lens.
- Size of the lens: Decides how much light can be collected, this means a bigger lens could collect more light, which massively enhances the image quality.
- Size of sensor: The key element of digital cameras, it determines factors like formats, resolution (number of pixels), accuracy, noise (Magnor 2015) and pictural quality. A bigger sized sensor can receive more light, therefore, it produces better quality images.

Figure 28. size comparison a DSLR (Nikon D5300) and a smartphone camera module (with 4x zoom in)

Considering these factors, DSLR cameras could produce better images with the same shooting conditions.

2.5.3 On-site preparation

Surface

Preparation is the key to success: after choosing the right photogrammetric strategy and equipment for the site, the next step is to prepare for shooting on-site. Specifically, some of the on-site physical conditions should be slightly modified into a suitable environment for photogrammetry.

The most important factor during on-site preparation is surface condition: receiving the light (which is reflected by the surface) with camera devices (camera sensor), the light information will be captured and further processed into digital images. Since the capturing process captures the light source from a material surface, it is important to understand how light behaves in terms of the material and its surface condition. Depending on the material and the surface, the way light reacts and behaves can be widely different. This behaviour can be generally described using four decisive properties (Hunter 2013): diffuse reflection, regular reflection, transmission and absorption (Fig.29). In practice, depending on the material and surface finishing, it determines if images can be gathered correctly for a further photogrammetric reconstruction process.

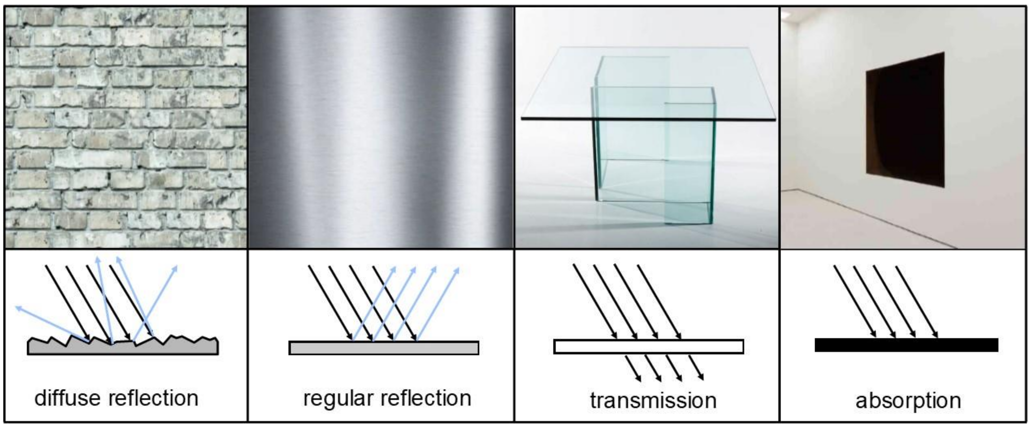


Figure 29. behaviours of light after engaging the surface

Taking pictures of surfaces with regular reflection, transmission and absorption, light is either directly reflected, passed through or absorbed completely. In other words, none of the surface information can be gathered correctly, which makes it difficult to evaluate the result using photogrammetry software. Fortunately, these surfaces are rarely present in historical buildings. Highly reflective, transparent surfaces like glass could be modified physically by applying a secondary non-reflective or non-transparent layer, or/and recreated digitally afterwards. Lastly, applying the polarizing filter onto camera devices could also reduce the reflection of the surface (Slama1980).

Lighting

Photogrammetry software become reliable nowadays, however, none of the existing software is capable of distinguishing shadow selectively for removal. Accordingly, shadow on building surfaces will be recorded as existing content during the image acquisition phase. Therefore, another important step in on-site preparation is to setup lighting to avoid overshadowed areas: if there is no light, nothing can be reconstructed at the end. Applying additional light sources for specific overshadowed areas is essential.

The ideal shooting condition is when the surface is rough (diffused reflection) and evenly lit without shadow, thus providing the possibility of gathering the most accurate result from the surface for the reconstruction process. It can be achieved particularly by diffusing the light sources or by using multiple diffused light sources. (Fig.30)

Another main reason for shadow avoidance is to prevent the shadow being reconstructed permanently on to the scanned object in the result produced in the photogrammetry reconstruction software: since reconstructions software cannot distinguish or remove shadow automatically, the shadow or overshadowed areas will be used as textures to map the reconstructed geometry. In this sense, it is advisable to record buildings from outside on an overcast day, when the sun is covered by clouds and produces diffused light naturally. In an indoor shooting environment, applying multiple diffused light sources and covering window areas with semi-transparent layer could reduce overshowed areas to improve the final scan result.

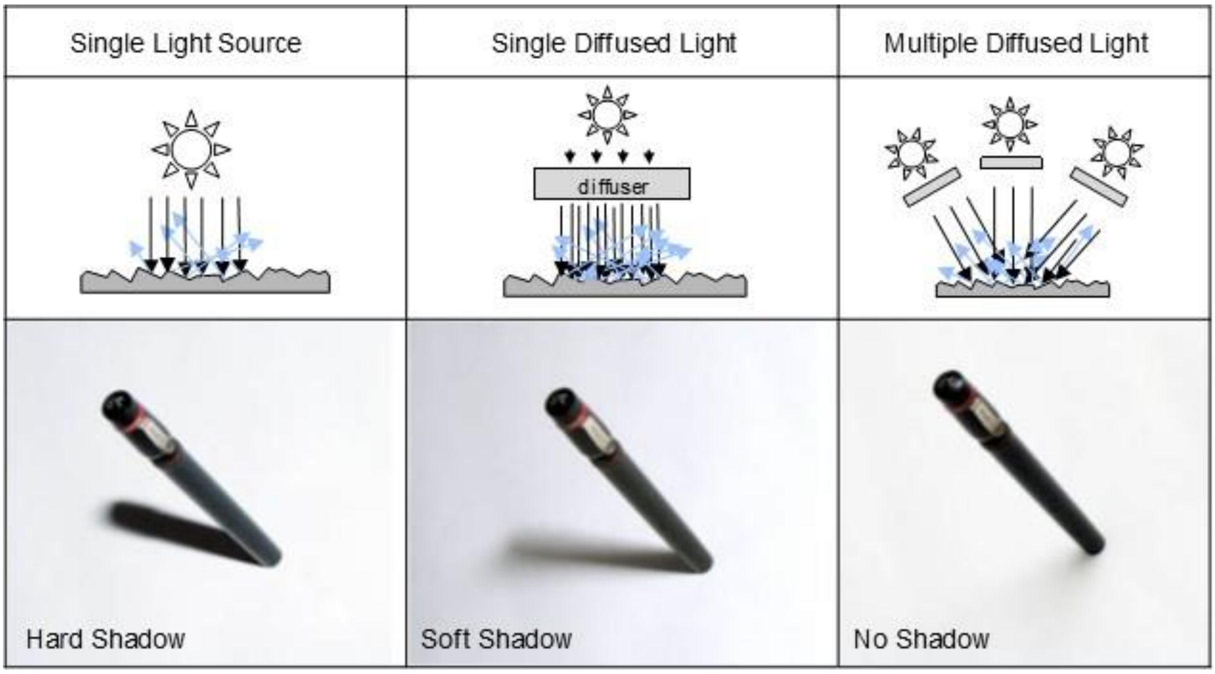


Figure 30. lighting scenarios with different lighting sources applied

Removal of covering objects and avoidance of moving objects

In practice, existing contexts are often in a poor physical condition and crowded with numerous objects. A lot of these objects are often not relevant for the building redevelopment process and should be removed from the site at the beginning. Moreover, since photogrammetry is not capable of recording any covered geometry underneath, objects covering the building surfaces should also be removed from the site. Lastly, photogrammetry is intended to record a static moment and the condition of objects; accordingly, any moving or changing objects (e.g. moving cars, people, flashing light sources) on site should be avoided (Fig.31).

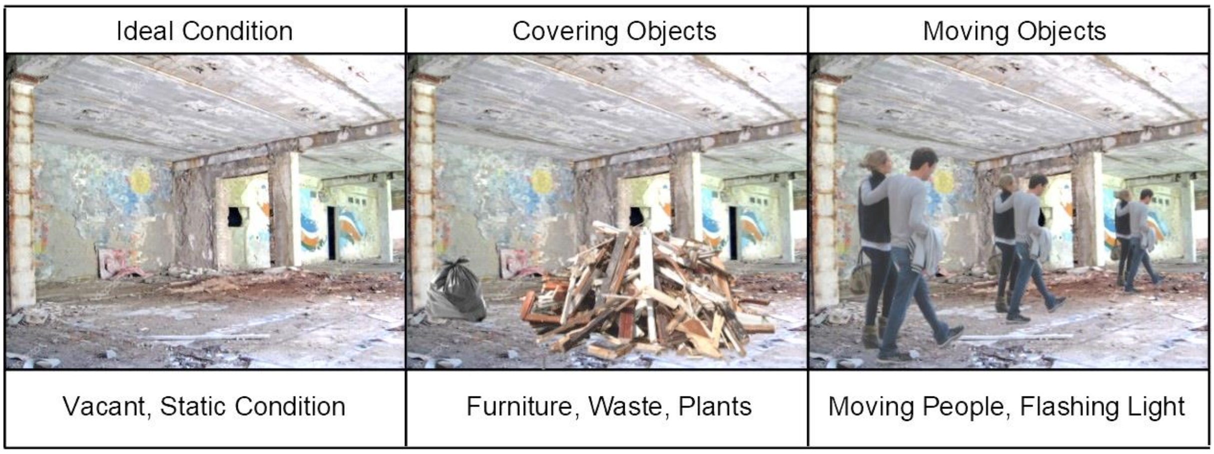
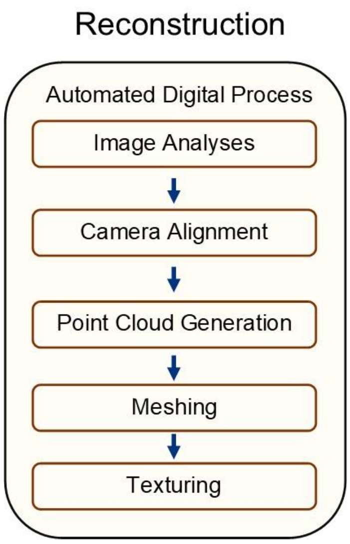


Figure 31. removal of covering objects and avoidance of moving objects

2.6 Reconstruction



The reconstruction phase is a complex mathematical and geometrical process. By combining principles such as computer algorithms into digital photogrammetry software, digital image reconstruction processes have become more accurate, automated and convenient. Specifically, popular accessible software like Autodesk Recap, Agisoft Photoscan and Reality Capture can achieve adequate results (Fig.32). At the end of this process, a textured 3D mesh of the building can be reconstructed. To understand the photogrammetric digital reconstruction process, the technical principle behind each step will be discussed in this chapter.

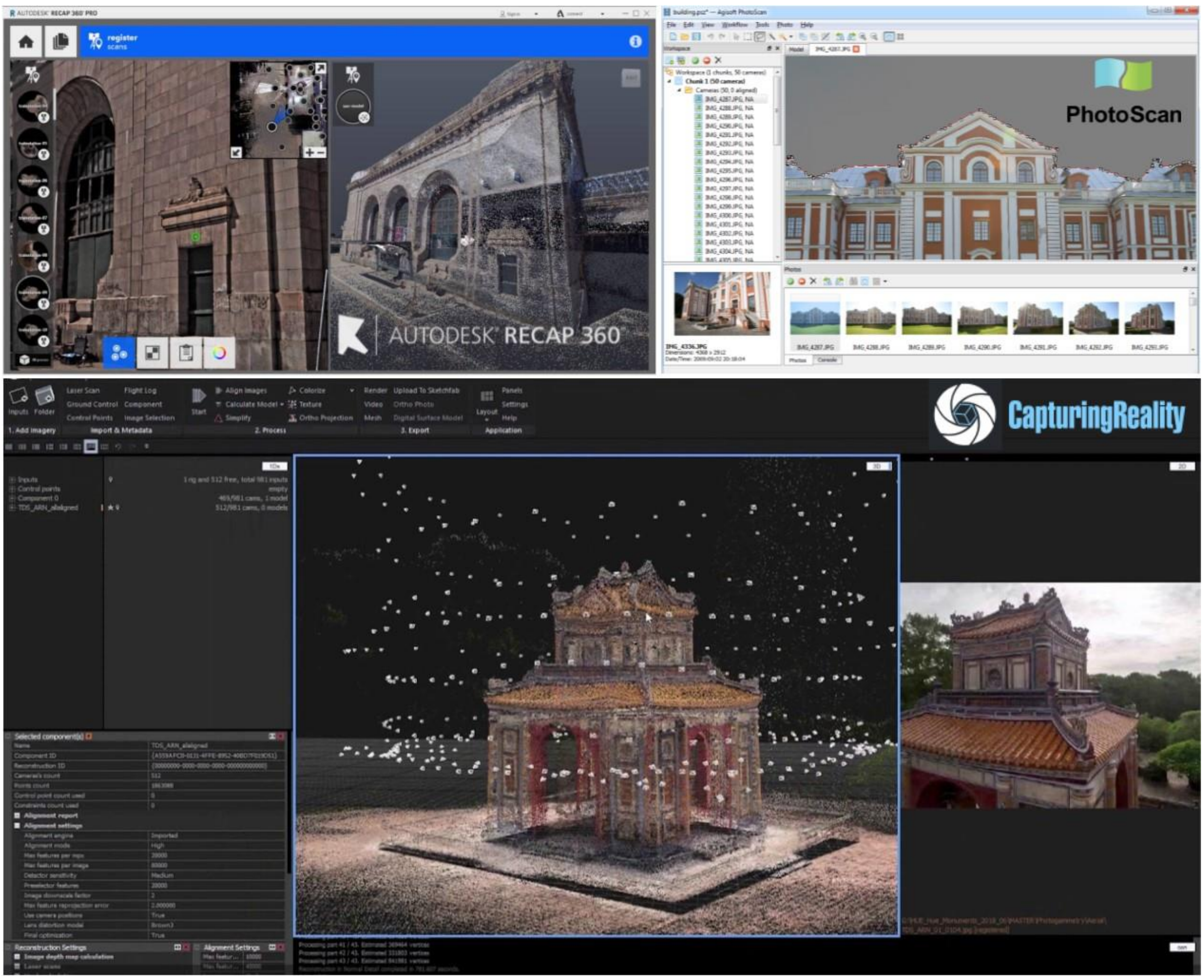


Figure 32. digital photogrammetry reconstruction software: Autodesk Recap, Agisoft PhotoScan, Reality Capture

Reconstruction software today is impressively capable: even processing random internet images which were taken by different persons at different times, and the reconstruction software is still able to accomplish the reconstruction (Fig.33) (Magnor15).

Figure 33. reconstructed 3D model: created from different random internet images

2.6.1 Image Analyses

The image analysing process relies on feature detection of images. Finding the unique, corresponding features of every single image allows the software to find the correspondences of images to each other in order to perform the reconstruction. It is necessary to understand the main characteristics of these features (Haralick 1992):

- Distinctness: Can be simply distinguished from background.
- Invariance: Independent from radiometric or geometric distortion.
- Interpretability: The feature should have meaningful mathematical values.
- Stability: Robust against picture noise.
- Uniqueness: Can be easily distinguished from other points.

To detect and to extract those features (points of interest), mathematicians, geodetics and computer scientists have developed different detectors such as the Förstner detector, Harris detector and Susan detector (Remondino 2006). These detectors use different formulas, composed as algorithms which are integrated into photogrammetric reconstruction software to accomplish the feature detection process automatically. These detected points of interest will be used as tie points to restore the correspondence between images to determine the geometry (Fig.34).

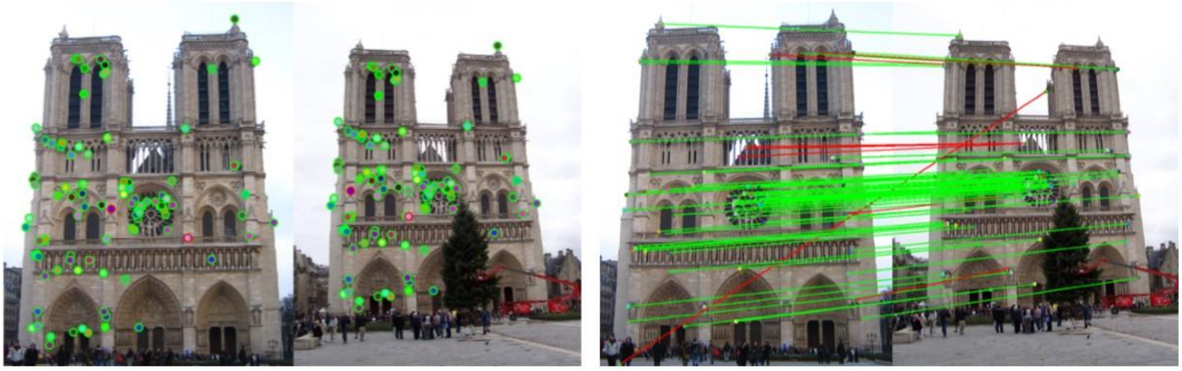


Figure 34. detection of feature points and its correspondance between images

Applying “control points”, which can be selected in software manually or by placing coded “markers” (also called “targets” or “tracker”) into the shooting scene: these pre-generated, coded markers with numerical information can be detected and decoded by software afterwards to accelerate the processing speed (Wijenayake 2014). (Fig.35)

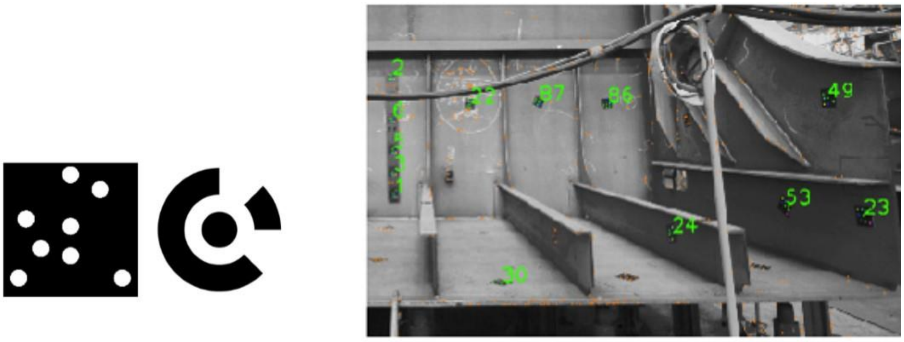


Figure 35. (a). dot distribution markers (b). concentric ring marker (c). automatic detection of markers

However, further reconstruction processes are based on feature points and this also determines the biggest weakness of photogrammetry: when taking photos of continuous monotonous, flat surfaces, like a white wall (Fig.36), or large painted surface area, often not enough feature points can be detected by the software, and thus it cannot be reconstructed successfully.

Figure 36. feature detection of monotonous, flat surface: less or none feature could be detected from this type of surface

2.6.2 Camera alignment

After providing photogrammetry reconstruction software with numerous images, the first step is to align the camera positions (from each image taken) based on feature points in a 3D system. The principle behind this process is simple, specifically, four key elements are required to accomplish the camera alignment process: the real physical existing point **P,** the projection-centre **O´,** the point on the projection (image) **P´** and the straight line that goes through them, the **Ray** (Fig.37).

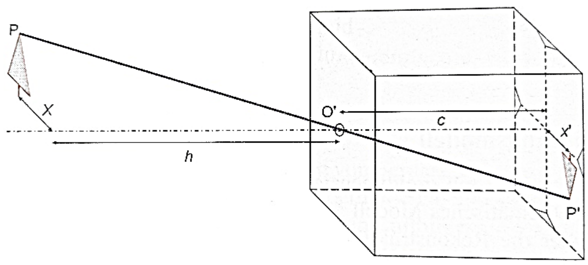


Figure 37. schematic demonstration of a pinhole camera (Luhmann 2010)

Following this rule, every picture has image points **P´** and the projection-center **O´** which both are known factors. In this sense, it is now possible to cast a straight line between them, which is the **Ray**. Till this stage, the camera positions are still unknown. However, modern photogrammetric reconstruction software is sophisticated, and after selecting a tremendous amount of unique image points **P´**, numerous bundles of **Rays** for each of the images will be generated; if two Rays, which are casted by the same point **P´** from two different images, intersect with each other, the geometry point **P** can be determined, and therefore the projection centre **O´** (camera position) can also be determined (Fig.38) (Luhmann 2010).

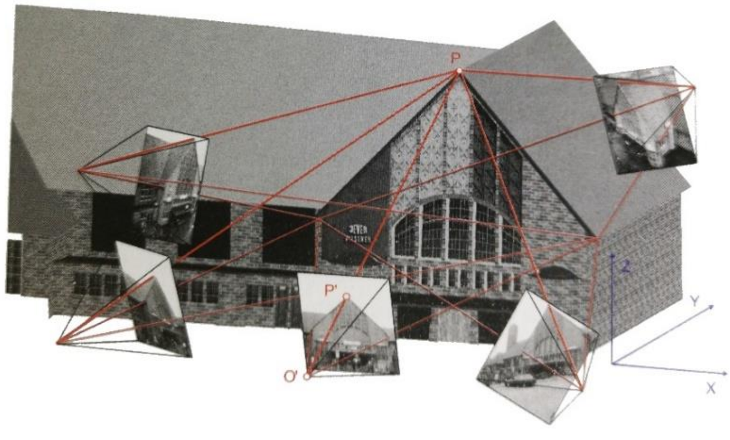


Figure 38. determination of camera positions based on bundle triangulation

2.6.3 Point cloud generation

With intersections of numerous ray bundles, not only are the camera positions determined, but tremendous numbers of intersecting points (vertices) are also generated (Fig.39). This accumulation of points is called point cloud, which represents the final geometry approximately.

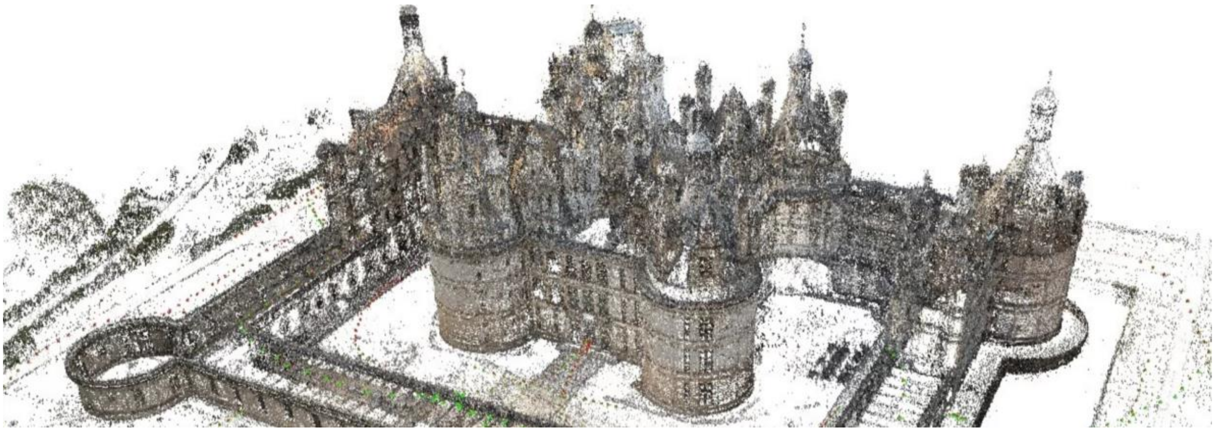


Figure 39. point could generation (@all3DP)

Depending on the size of the scanned structure, the number of points in this dense cloud could reach over 100 million, which is not convenient for practical uses. In architectural application practices, since not all these vertices are required, and for a better computing performance later on, it is necessary to reduce the count of vertices into a much smaller, desired number (~ 1 million). This simplification process can be achieved by an integrated function in the reconstruction software, which allows users to precisely reduce the number of the point cloud in a non-destructive way. The principle of this simplification process is straightforward (Hao 2007): the whole data set of vertices will be divided into a fixed number of "clusters", each cluster will be evaluated and then represented with one new intermediated point (Fig.40). As a result, a simplified point cloud with much fewer vertices will be generated. It should still be dense enough to represent the geometric form for the further meshing process.

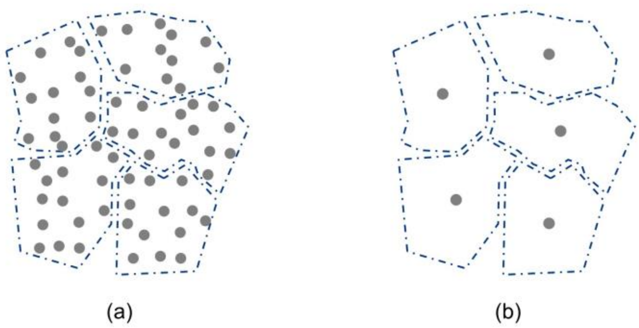


Figure 40. (a). clustering of points into sections (b). each section will be represented with only one newly created point

2.6.4 Meshing

Visualization of a dense point cloud represents the geometry in a decent way, however, each of these vertices only contains its coordinate (X.Y.Z) by itself. To obtain a 3D geometry determined by these coordinates, its necessary to connect (mesh) these vertices with the triangulation method: By connecting the vertices with smaller triangularly meshes, a single large connected closed mesh (polyhedron) can be generated (Pottmann 2007). The most common method of triangulation is called “Delaunay-Triangulation” (Fig.41): every circumscribed circle from three points must not contain another point (Luhmann 2010).

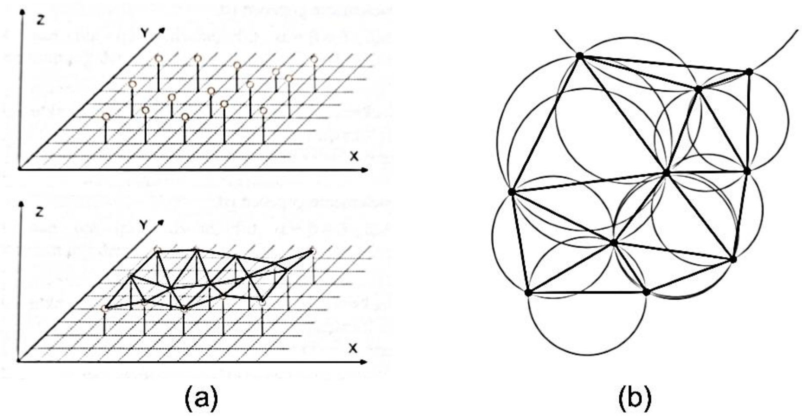


Figure 41. (a) meshing from points with triangulation method (b) principle of Delaunay triangulation

By applying the triangulation method, coordinates of vertices will be described as a solid geometry, which is essential for the further digital process. This approximation and subdivided version of geometry with triangles has the advantage (Fig.42), that each of the triangles is planar. And the planarity of surfaces is the key element for the further digital operation, like texturing.

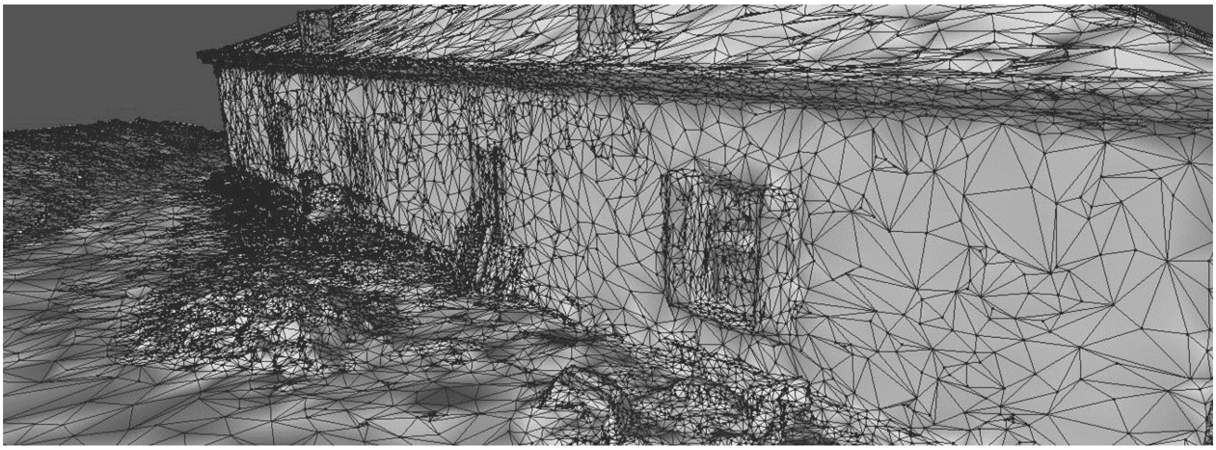


Figure 42. triangularly mesh generated from point cloud (@Wesmapping)

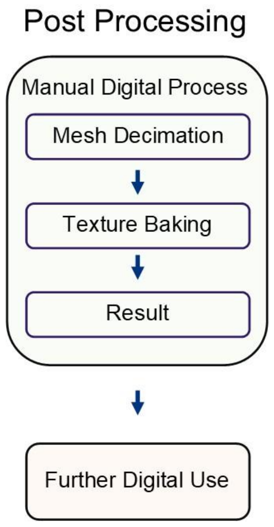
2.6.5 Texturing

The last step of the reconstruction process is to visualize the geometry which is obtained from previous steps, this can be achieved by texturing the geometry. The locations of cameras and geometry are both known factors. Accordingly, it is possible to reuse the picture to project it onto the geometry surface.

Specifically, as each of the triangle coordinates is a known factor, it is possible to find the corresponding camera position, which is also a known factor. Using projective transformation, part of the image (boundary defined by the outlines of the triangle) will be located, isolated, distorted and projected onto the corresponding triangle surface. By doing this process repeatedly, all the triangles will be textured with original images. This textured geometry now represents the building geometrically and visually (Fig.43).

Figure 43. comparison of model mesh and textured model

2.7 Post Processing



The main goal of post processing is to simplify the complexity of the model with as little loss of detail (geometrically and visually) as possible, or no loss. As the textured mesh is generated in the photogrammetry software, the photogrammetric reconstruction process could be considered done. However, the initial generated textured model is often not compatible with further digital usage by other software, and in this sense, the initial model from the photogrammetric reconstruction software must be further processed.

Post processing is a complex computer graphical work, and professional specialists like 3D artists and digital visual artists are often required in practice to achieve the best result. However, with sophisticated software, architects and other creatives could obtain adequate results.

2.7.1 Mesh decimation

Mesh decimation or mesh simplification is the process to reduce the number of triangles (polygons), without losing the essential approximated shape (Fig.44). With a reduced number of polygons, the simplified mesh demands less computing power and is more efficient to render. By performing serval different mesh simplification algorisms like vertex decimation, edge collapse, etc. (Mukundan 2012), it is possible to reduce the polygon into a specific desired number. In practice, several sophisticated software tools such as: “Z-Brush”, “MeshLab” and “Instant Mesh” with integrated algorithms can manipulate and decimate the mesh in different ways until the desired result is reached.

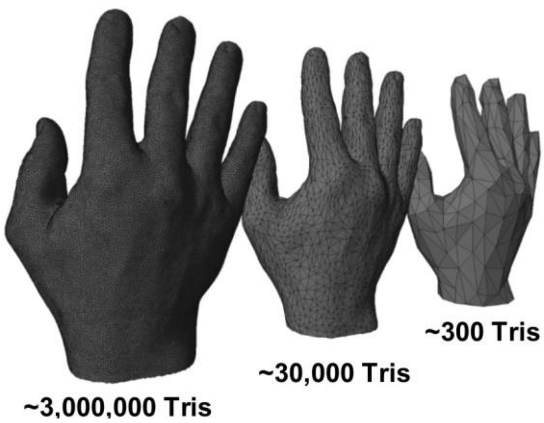


Figure 44. mesh simplification, from left to right, non-simplified, simplified, and strong simplified mesh (Cacciola 2007)

2.7.2 Texture Baking

A simplified mesh (low-resolution mesh) represents the non-simplified geometry (high-resolution mesh) approximately, however, the low-resolution mesh has lost a huge amount of surface details. To compensate for the loss of details, a technique called "texture baking" could be used to keep the level of visual detail in high-resolution mesh for the low-resolution mesh (Dörner 2013). The principle of this technique is to generate collection of texture maps (normal map, ambient occlusion, etc.) that describe the properties and quality of 3D models (Inglese 2018). After applying the collection of texture maps onto the low-resolution mesh, the details (texture, reflection, light, shadow, etc.) from the high-resolution mesh will still be represented on the low-resolution mesh (Fig.45).

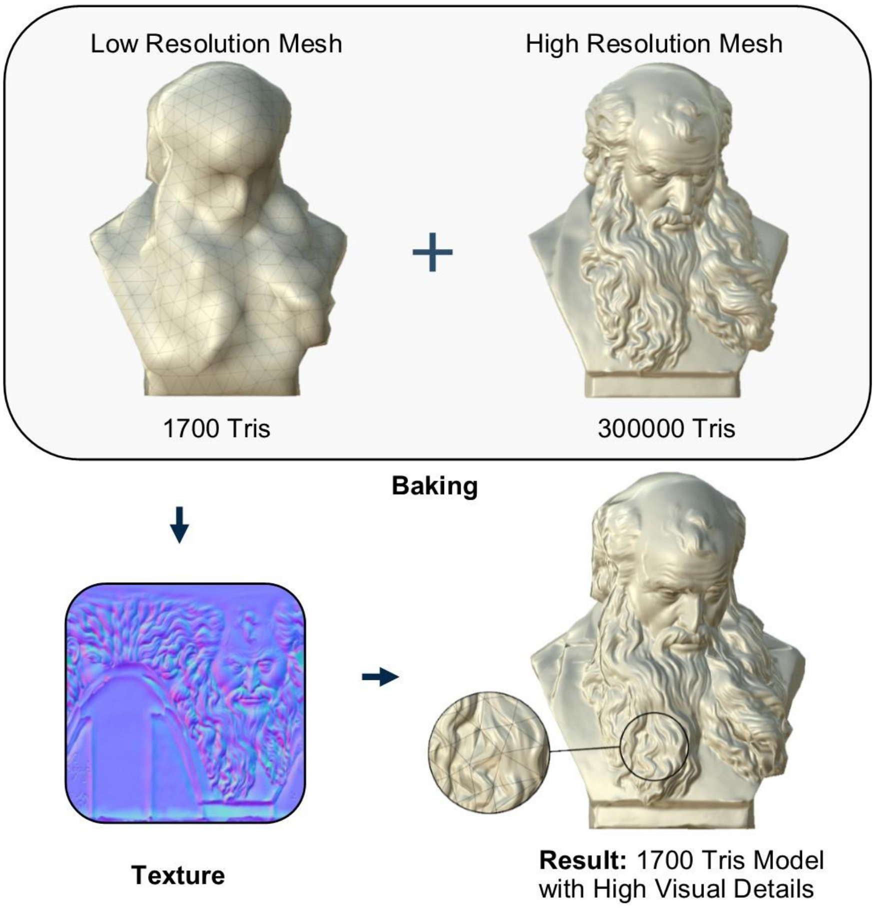


Figure 45. texture baking process

Texture baking is the most common technique widely used by computer graphical related disciplines, which allows users to bake the texture in a highly automated way. The final result, the almost visually identical textured low-resolution mesh model, can be generated and be used in diverse digital platforms (e.g. VR) without loss of visual quality.

2.8 Advantages of applying photogrammetry

With photogrammetry, the subject can be recorded by gathered images, which are able to reproduce the location, geometry and textures. Architects could review the site in a more detailed and realistic manner than using the traditional recorded plan. In other words, architects could review a digital replica of the site, in which even the smallest detail will be displayed in its natural condition. It allows not only architects but also other related disciplines (e.g. structural engineers) to review the site and plan precisely. Furthermore, the possibilities of plotting vectorized plans using photogrammetric data and reusing the generated model for visualizing and representation are also helpful and save time.

Photogrammetry can be compared with another popular survey recording method, laser scanning, which could achieve the same (or an even better) result. However, laser scanning requires invariably expensive equipment and specially trained operators to operate, whereas a photogrammetric scan could be performed by architects without any extraordinary equipment or hardware required. With continuous developments like:

- Improvements in mobile digital image-taking devices
- Sophisticated software that automates and combines the whole reconstruction process into one single software tool
- Improved computing power

photogrammetry scans become a low-cost, easy to apply, and highly efficient scan method which outstands laser scanning in practical uses.

Integrating scan data into VR gives architects even more accuracy and possibilities for re-engaging with the environment. It is also conceivable that the application of photogrammetry not only serves a purpose as a documentation tool, but is also the basis for building designing and presentation methods in a single workflow during the building redevelopment process.

2.9 Example of photogrammetry applications

Depending on the size and complexity of the object, with the suitable equipment and right shooting strategy, architects could obtain extraordinary results with the application of photogrammetry. The following examples from Pix4D on SketchFab demonstrate the capability of photogrammetry applications (Fig.46 -Fig.49). Moreover, these highly detailed, textured 3D models could also be further used for any thinkable digital purposes (e.g. 3D printing).

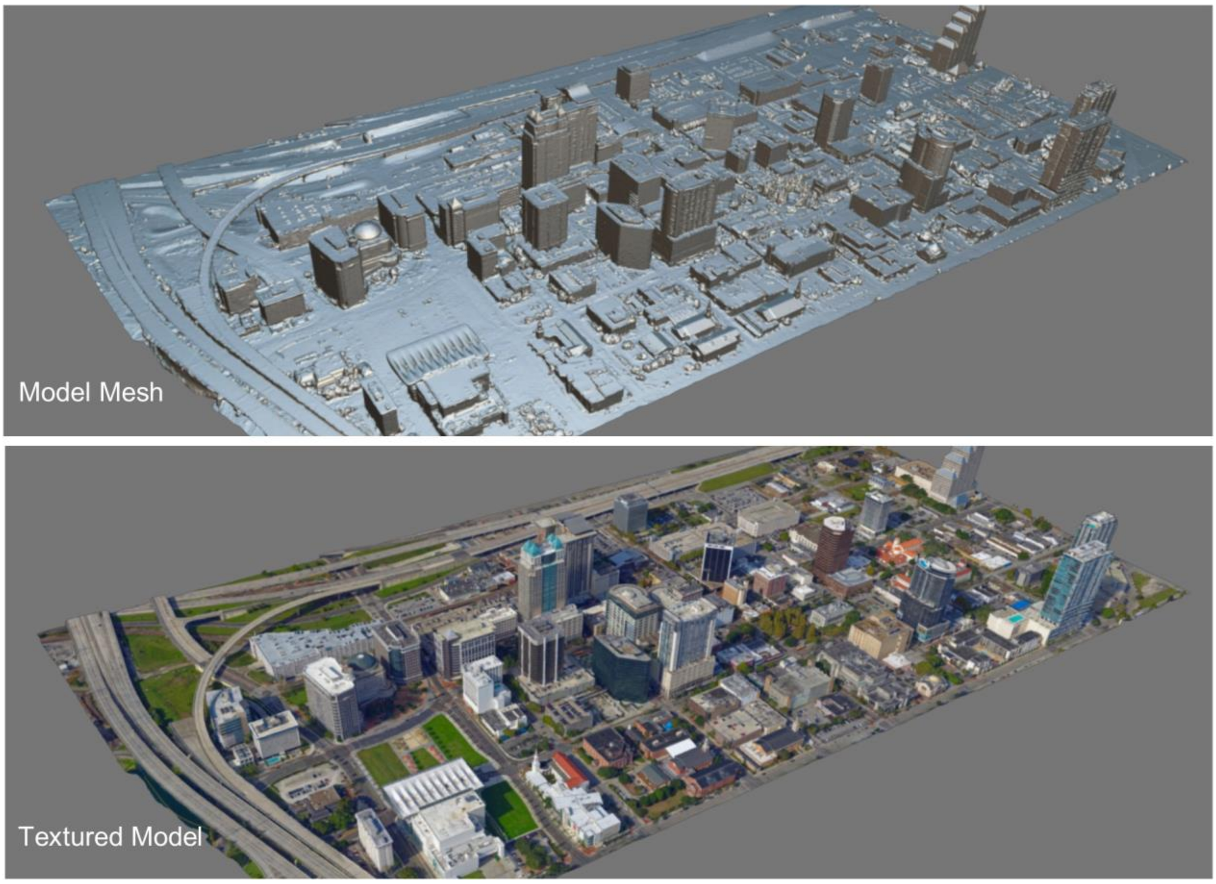


Figure 46.result of aerial photogrammetry application to the city of Orlando, USA.

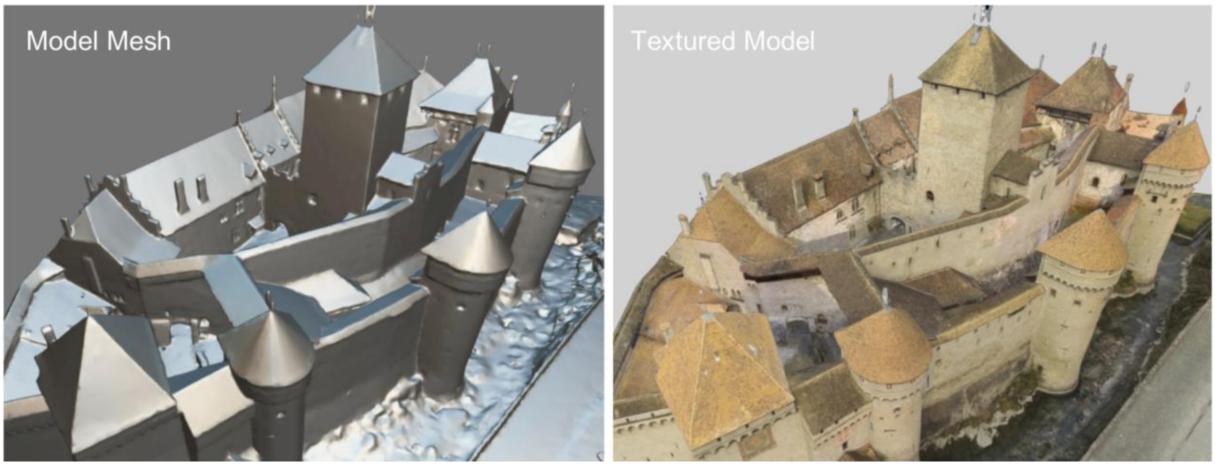


Figure 47. result of terrestrial/aerial photogrammetry application to Chillon Castle, Switzerland.

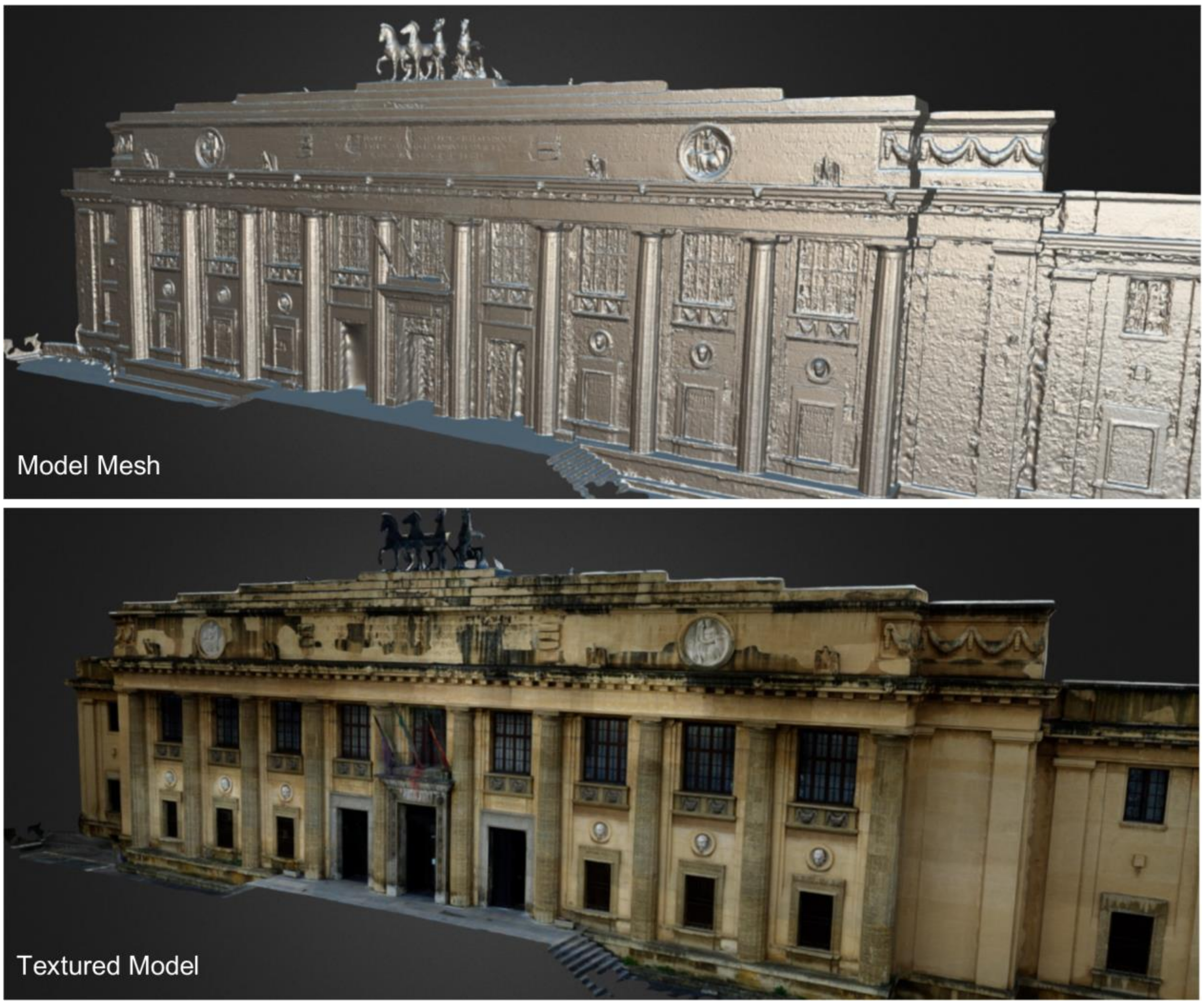


Figure 48. result of close-range photogrammetry application of Palazzo Piacentini, Messina.

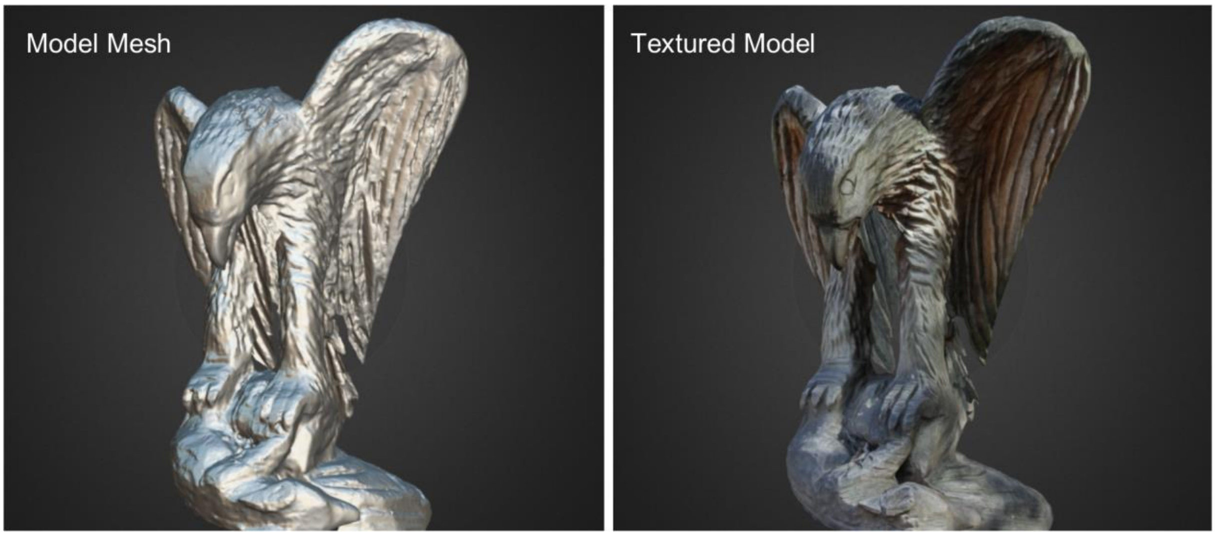


Figure 49. result of super close-range photogrammetry application to building element.

CHAPTER 3

Virtual Reality as an architectural design and presentation tool

Humans use drawings to describe surroundings, events, and ideas. Describing things by drawing is part of the human nature and it is especially important for architects. Architects kept drawing analogously till the end of the 1980s, when the upcoming Computer Aided Drawing (CAD) software was first used. With help of CAD, digital operations like “draw line”, “delete”, and “rotation” replaced the arduous task of physically drawing with pen, ruler and eraser. Besides the time-saving factor, CAD encouraged architects to design more complex forms and shapes in larger scale, which is nearly impossible to do analogously. With software development, CAD became a state-of-the-art method for architects during the planning process. As most CAD software are 3D based systems, architects could study their design from different viewing angles and perspectives on a monitor screen.

However, the current architectural workflow is still mostly 2D based and is determined by the traditional tools used nowadays. Specifically, though the CAD software system is 3D based, due to the 2D output interface (monitor), architects still only experience the 2D illustration of a 3D space. In other words, architects could not obtain a true experience like “standing inside it”, instead of imagining it (Fig.50).

Moreover, pictorial illustration like architectural rendering can only give one static illustration of the design in a 2D medium. Lastly, a 2D plan is indeed accurate, but it is difficult to communicate with others based on the information content of one single plan. Certainly, with physical build models, architects can investigate the design in 3D space, though, since physical models are mostly built as extremely abstracted versions in a much smaller scale, it is difficult to study the design entirely based on models. Especially the interior of a building with numerous details can often not be built physically as a model, so this still relies on the imagination of the architect.

Another major disadvantage of these physical medium representation methods is the scale. Specifically, architects have to downscale the design idea into 1:100, 1:200 or even 1:1000 during the design process, and while the dramatic abstraction of the design idea is practical for the design process, the desired scale 1:1 could not be achieved with these traditional physical media due to the time and effort that would be required.

Figure 50. current architectural design and presentation methods and tools

With the application of virtual reality, which has already proven its advantages in education, medicine and other professional applications, modern architects could also use this platform to be “present” in the virtual environment. Switching the design platform from monitor/model into a Virtual Reality system allows architects to inspect the building conditions, perform design operations, review design results and use it as the presentation tool inside a “true” 3D environment.

3.1 Virtual Reality overview and development

The term “virtual reality” is used to describe imaginary worlds which only exist in the mind. Since VR is not only a technical term but also a philosophical and perception-linked term, the scientific definition of virtual reality has been long discussed and continuously renewed. In 2015, the field of study defined VR as:

*“an **artificial** environment, which is experienced through **sensory stimuli** (as sight and sounds) provided by a computer and in which one’s **actions partially determine what happens** in the environment.”* (Jerald 2016)

Another alternative reality is called augmented reality (AR), since the AR hardware device could look similar to hardware applied in VR, it often causes confusion in practice. To differentiate it from augmented reality (AR), it is necessary to take a look at the taxonomy of alternative realities relating to AR and VR (Fig.51):

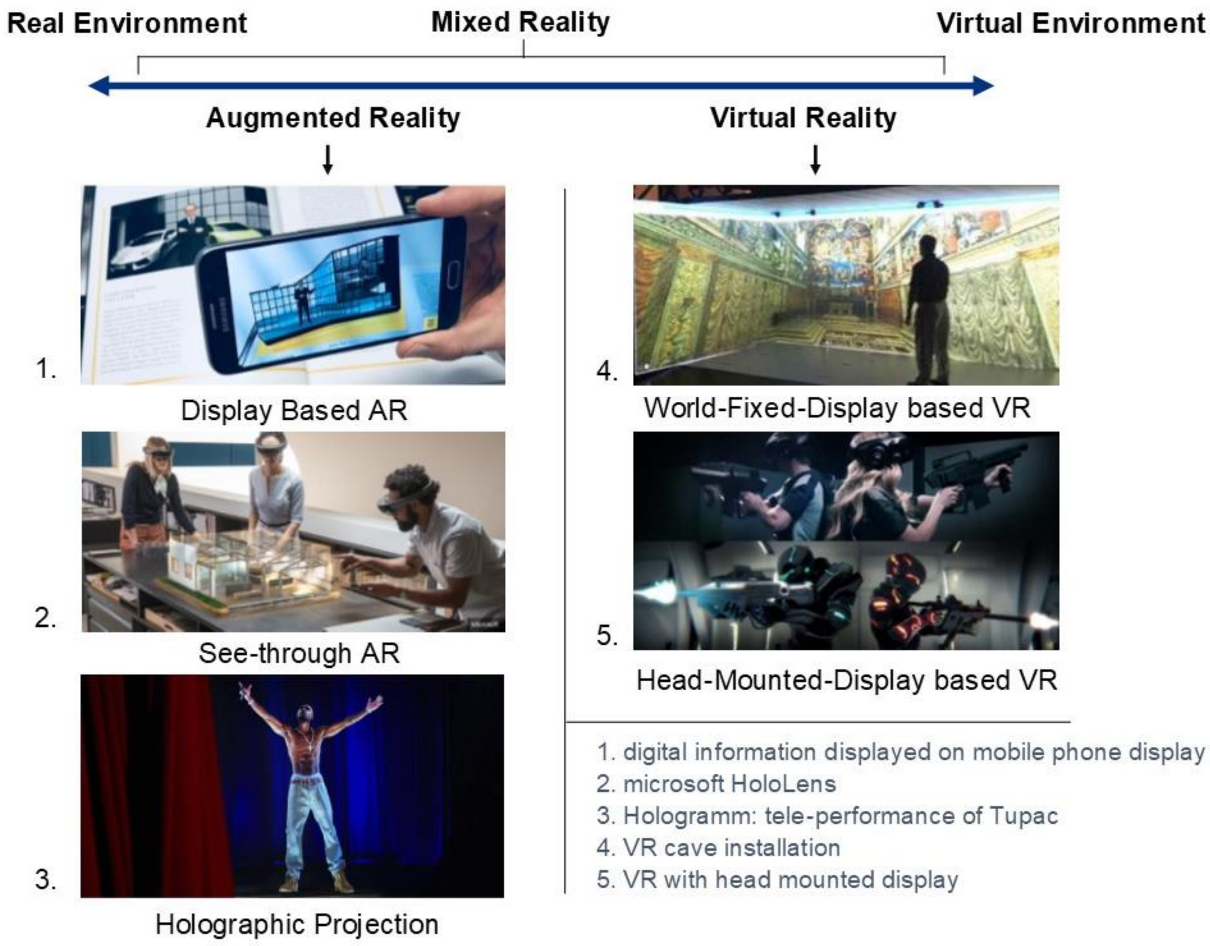


Figure 51. taxonomy of mixed reality

Specifically, augmented reality adds digital contents onto the real world as additional information, on the other hand, virtual reality creates an artificial world and its content as a digital computer-generated environment. To understand VR, some ground-breaking milestones in VR development and some recent accomplishments will be introduced.

Sword of Damocles ~ 1970

The first ground-breaking point in VR development came with the invention of the "Sword of Damocles" system in 1968 by Ivan Sutherland (Fig.52), which was the first true computer-mediated virtual reality system, which had the first "BOOM" (Binocular Omni Orientation Monitor) display. At that time, the system was only able to display a single wireframe of a cube to the viewer's eyes, and the system was so bulky so that the system had to be mounted on the ceiling, reaching the viewer's head with an adjustable pole. The Sword of Damocles is considered as the precursor to all modern digital virtual reality systems.

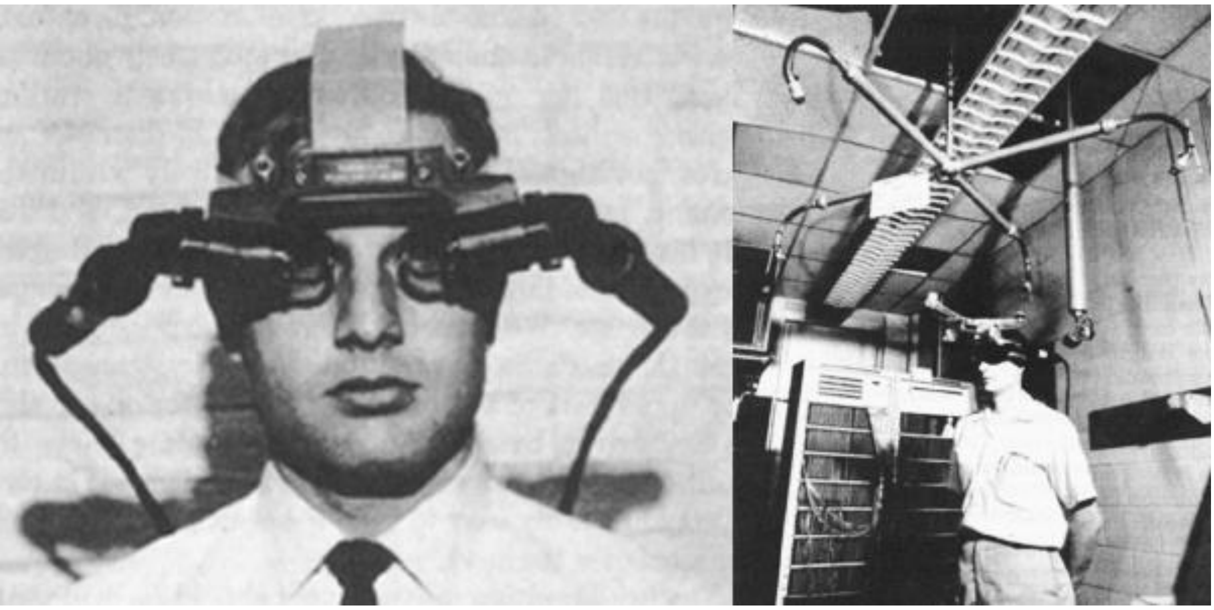


Figure 52. Sword of Damocles, 1968

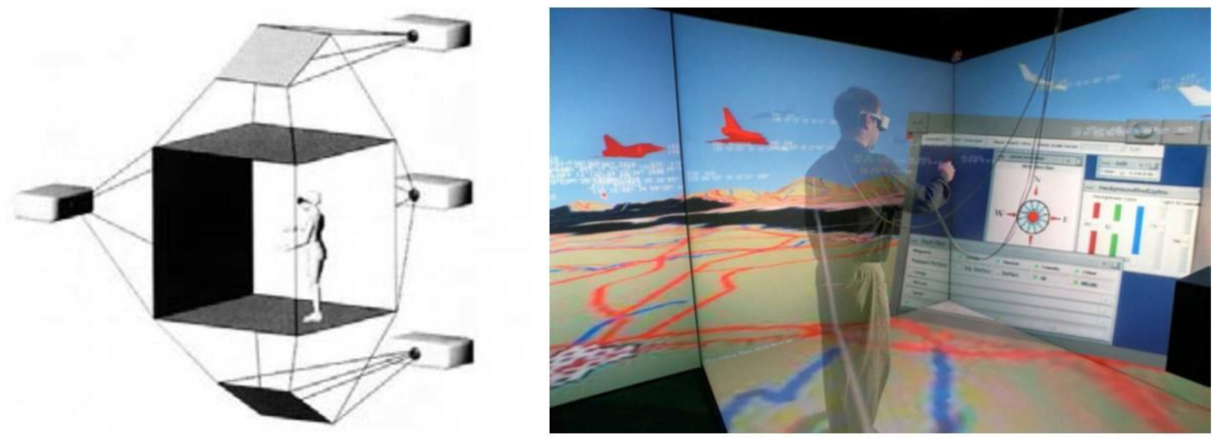
VIEW ~ 1980

Computer scientists further developed the VR system by integrating better tracking systems and input/feedback devices (e.g. glove) and gave the VR system a practical use. In 1989, NASA introduced their VIEW system with a much smaller stereoscopic head-tracked head-mounted device (HMD) with an innovative "power glove" as the controller (Fig.53). This VR system was developed as VR training simulation for astronauts.

Figure 53. NASA VIEW system, 1989

CABANA ~ 1990

Other VR techniques are based on world-fixed displays instead of head-mounted display. The so-called “VR-Cave” uses world fixed displays (e.g. arranged monitors or projections on the wall and floor) to create the artificial environment. Specifically, VR-Cave CABANA uses projection on moveable walls to create an immersive VR experience. (Fig.54) However, this method is often more expensive and requires more physical space.



(a) (b)

Figure 54. VR-Cave CABANA: (a). schematic functional principle by using projection (b). User inside of CABANA

“VR winter” ~ 2000

The first decade of the 21st century was a stagnant time for VR development. Although there were several VR research studies carried out in the field for academic and military purposes, the lack of an affordable head-mounted device with wide field of view, and insufficient computing power hindered the development and practical application of VR. (Jerald 2016)

FOV2GO_Boom of consumer VR HMDs ~ 2010

With the introduction of Field Of View To GO in 2012, this low cost open source HMD with wide field of view accelerated numerous developments in consumer HMD. Therefore, FOV2GO is also considered as the precursor of most of today’s consumer HMDs (Fig.55). Shortly after the introduction of FOV2GO, Oculus Rift Kickstarter was formed and became the most successful VR device manufacturer and research centre.

Figure 55. FOV2GO as precursor of today's consumer HMDs

Recent

In 2015, another low-cost multi-user immersive VR system was developed at the Technical University of Vienna. This system allows multiple users with mobile VR gear (backpack and HMD) to experience VR in a large/unlimited scale space. The essential advantages of this system are the boundarylessness of users and the space, with the help of trackers, so users can orient, touch and feel physical objects inside the VR environment and move freely. Moreover, the VR representation of users themselves via avatars is a communicative way to experience a virtual environment which also has social potential in terms of practical uses (Fig.56).

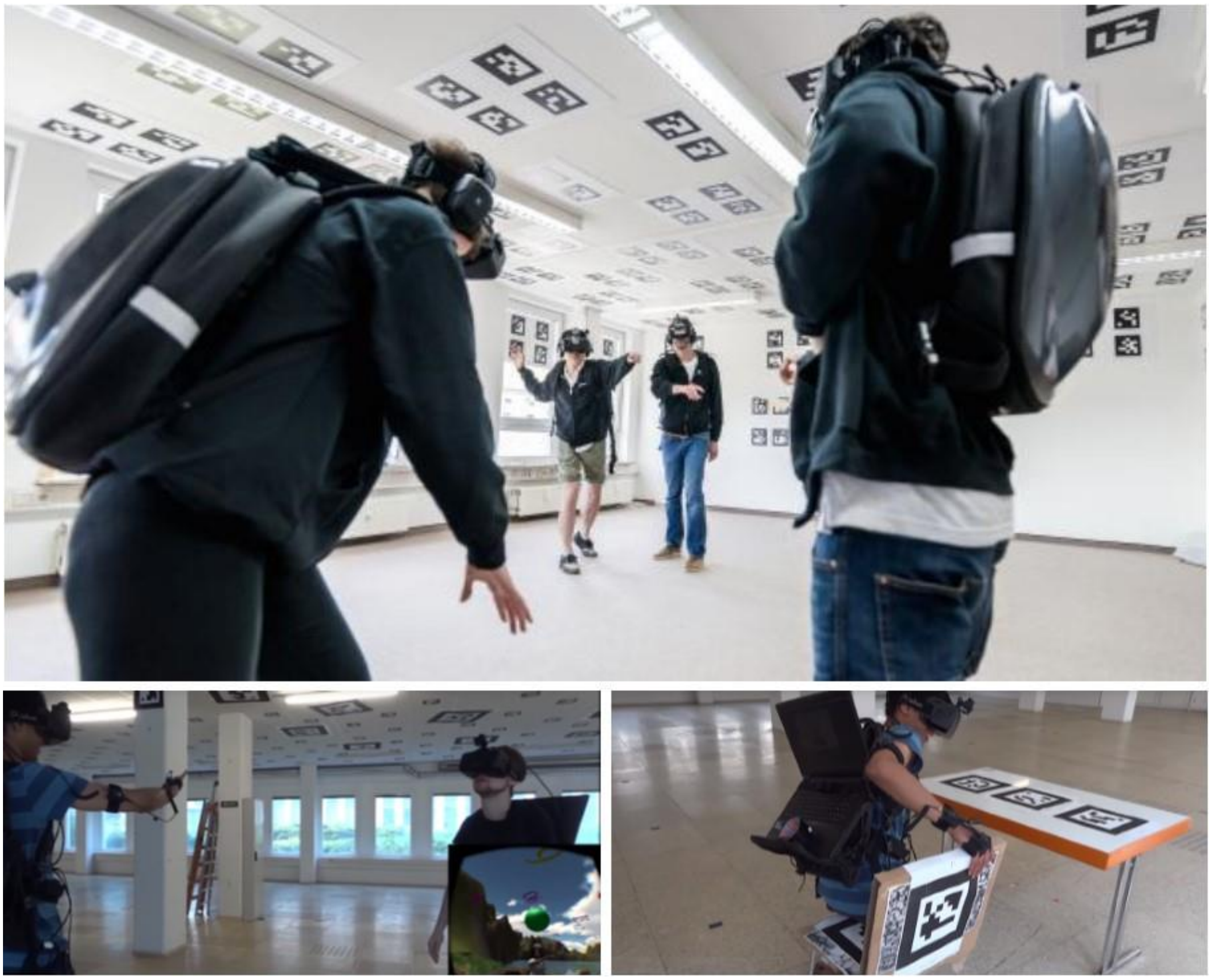


Figure 56. immersive deck, multi-user large-scale VR environment. (@ TU Wien)

3.2 Technical background

With increased computing power and better factory methods, VR systems became more practical and affordable. Despite the widely different forms and capability of VR systems, the fundamental principle of VR always stays the same: to simulate the artificial space by manipulating the human perception of space and having the possibility to interact with the virtual environment.

In this thesis, to study the feasibility and capability of VR application, the most affordable, HMD-based VR will be investigated and applied. To understand the functionality of this technology, it is necessary to understand the technical principle behind it.

The most important factor for achieving the immersive experience of "presence" is the perception of space from the point where the observer is standing. To achieve this goal, one simple but sophisticated trick of illusion is used by HMD-based VR systems: as human perceive 3D space through two different images (monoscopic) which are naturally captured separately by the left and right eyes, and which are further processed in the brain (stereoscopic) to give a sense of presence and dimensionality. VR systems use head-mounted devices to blend out the natural context and produce two different digital monoscopic images which are displayed separately in the left and right human eyes. By doing this, the observer senses the digital outputs as a "real" existing context and their own presence inside this artificial environment (Fig.57).

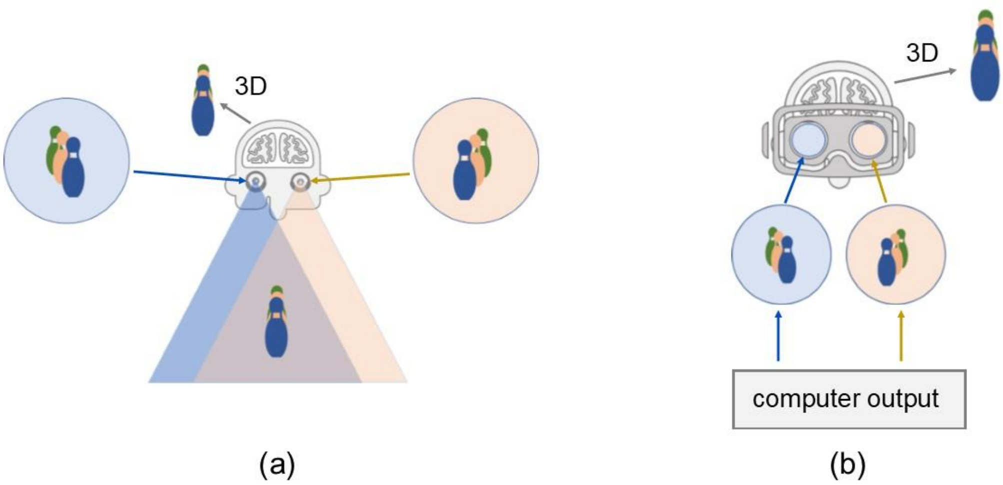


Figure 57. (a). natural perception of space. (b). artificial perception of space by using HMD from the VR system

However, producing a digital stereoscopic image can only provide one static moment of the sense of the virtual environment, since human perception of the environment is continuously changing based on head/body movement, and the environment also changes based on human influences (inputs). Therefore, different corresponding devices are used for the VR system to achieve the best immersive experiences. These can be generally described as (Fig.58):

- Head-mounted device: Output device which displays the artificial images produced by computer.
- Controller: The Input device to interact with the virtual environment.
- Tracking system: Tracks the position and rotation of the HMD, the controller, the human body and their relative positions to each other.
- Computer: Responsible for processing the data and continuously rendering images for the HMD.

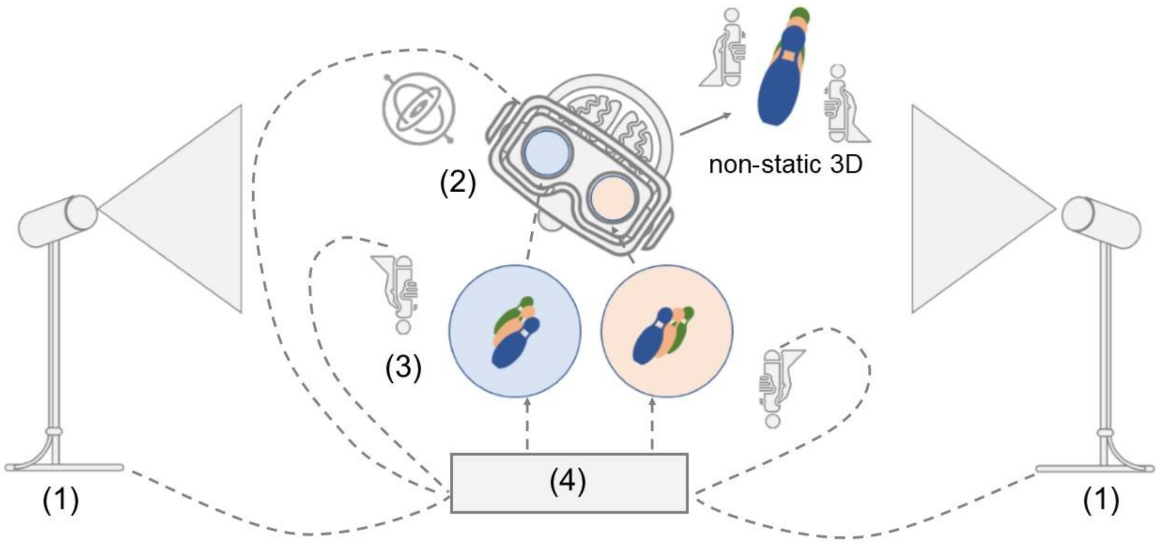


Figure 58. schematic demonstration of a VR system. (1). Tracking System (2). HMD with gyroscope (3). controller (4). computer

These hardware devices function and correspond with each other to produce continuous digital stereoscopic images based on the position. movement and rotation of the body, head, and hands of the observer. By doing so, the observer not only senses one static virtual environment, but rather an entire artificial reality, which the observer is able to correspond with.

3.3 Virtual reality workflow

The VR workflow could be considered as “stage design”. The idea is to build a convincing artificial VR “stage” which offers content for the observer to experience and interact with. The main goal of VR development is to build a VR application for VR hardware. Development of VR application is a complex process which combines hardware, software, and application development into one final product. In practice, the development of professional VR applications is complex and often requires multiple development teams solving specific tasks, a process that takes a long period of time to be achieved.

However, with the free version of game engine software, a software development kit (SDK) of VR hardware and numerous digital assets, architects are able to design their VR environment and publish the result as a VR application. To understand the whole VR workflow, it is essential to understand the basic components and technical background of each step during this process (Fig.59).

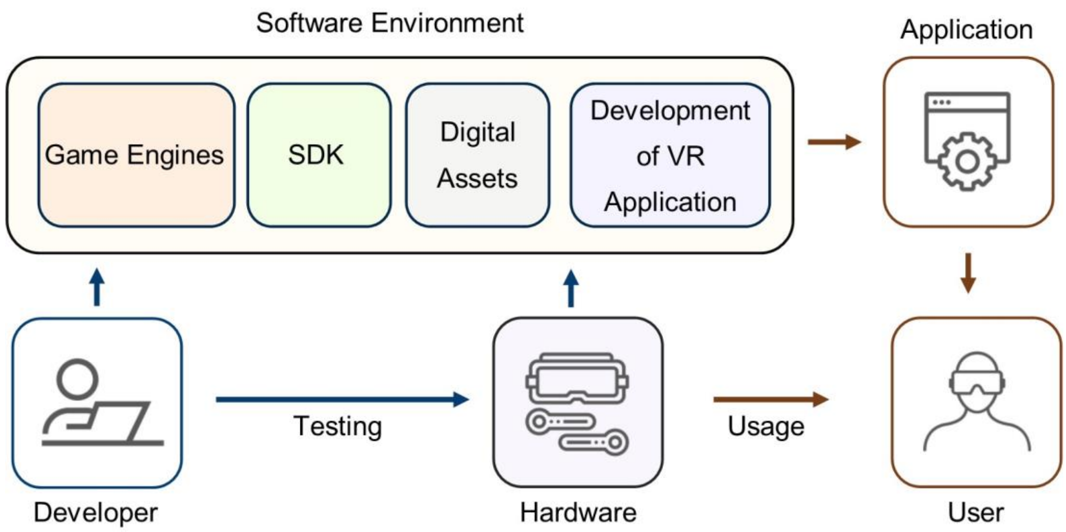


Figure 59. schematic demonstration of VR development workflow

3.4 Hardware

Hardware is one important component of the whole virtual reality workflow, and specific VR equipment should be defined as the first step of the workflow. VR equipment is the hardware devices (HMD, controller, tracker, etc.) used by developers to test the application during development and later used by users to experience the application.

The main purpose of VR hardware is to display the rendering content on the HMD and to track the position and register inputs of the user during the VR application usage (Fig.60).

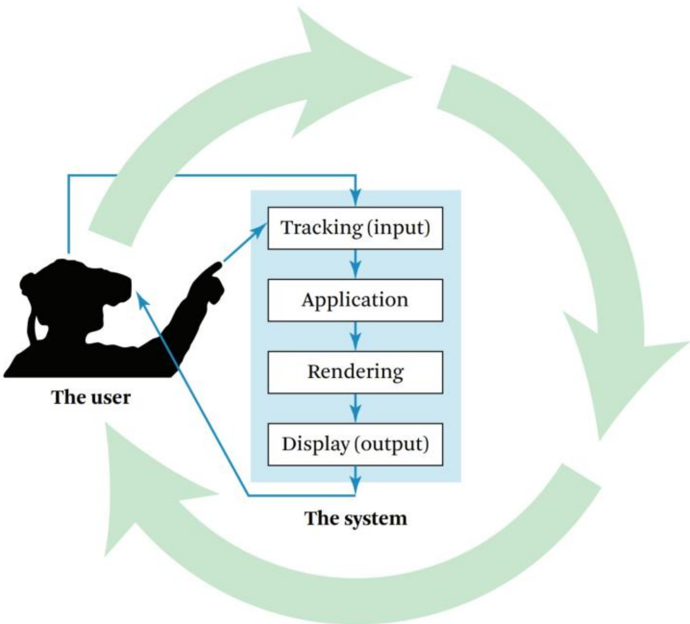


Figure 60. schematic demonstration of using VR application

On the consumer market, VR devices are designed, manufactured and sold by different companies as bundles. From the location where VR systems can be used, these can be categorized into two categories (Fig.61).

- Static VR system: Often comes with full equipment like HMD, tracking devices, and controller, which are physically connected with the computer. The most common static VR systems are the "Oculus Rift" and "HTC Vive".

- Mobile VR system: Has no physical boundary and could be used everywhere. The most common version is the “smartphone case” version, in which the user inserts the smartphone into a HMD “alike” case to produce and display the stereoscopic pictures. Another popular upcoming mobile VR system is the stand-alone VR device (e.g. “Oculus Go”), which has an integrated lens and processor to produce and display stereoscopic images.

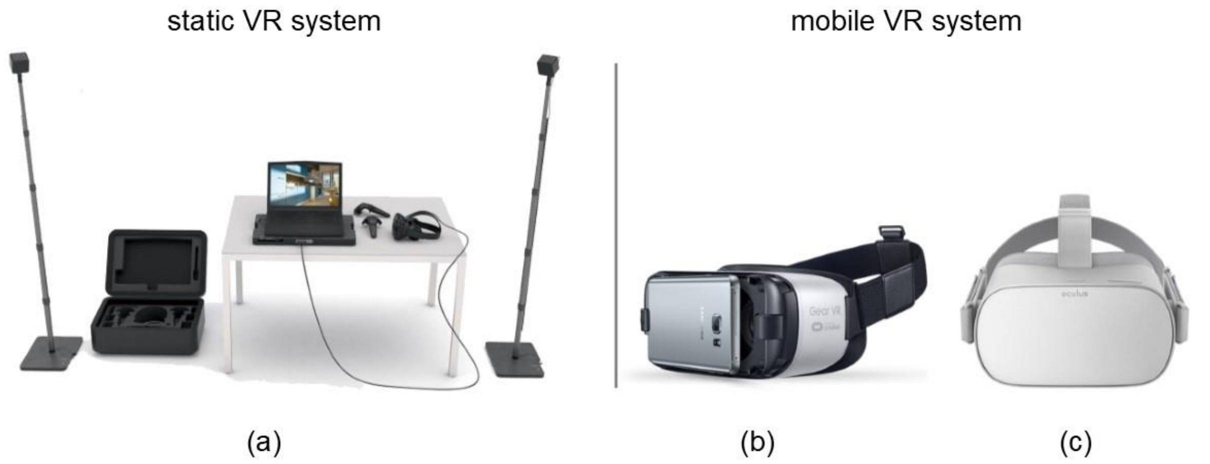
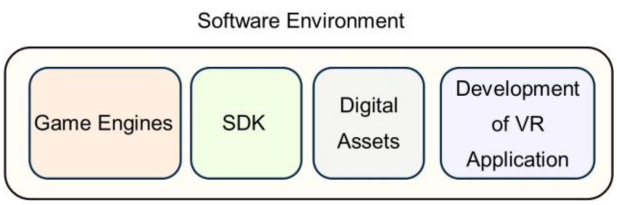


Figure 61. static and mobile VR system: (a). HTV Vive with computer (b). Smartphone-case mobile VR system: Samsung Gear (c). Stand-alone mobile VR system: Oculus Go

Although these mobile VR systems look promising based on its flexibility and much cheaper price, these can not deliver the best immersive VR experiences due to their limited computing power, display quality, and tracking possibility. Therefore, the mobile VR systems are primarily used for entertainment purposes.

In this thesis, to provide the best immersive experience possible, the static version of the VR system will be used for further development. Since the cost of equipment is one important factor of feasibility, therefore, only consumer-level hardware will be used in the practical part of the work.

3.5 Software environment



In the architecture domain, the fastest way to create VR environments for architecture purposes is by using BIM (Building Information Modeling) to VR software. These allow architects to import 3D models into pre-defined virtual environments to create a predetermined VR walkthrough (Sampaio 2018). However, these pre-made software often have limited quality, capability and varieties, in other words, users are only capable to perform action, if the premade software allows users to do so. Therefore, to create immersive, limitless VR environments, the most convenient way is to use a game engine as the VR development platform. Moreover, with the help of a software development kit (SDK) and usage of digital assets, architects could create any virtual environments in accordance with their own ideas and specific purposes.

3.5.1 Game Engines

A game engine is the framework system for the creation and development of video games. Game developers use game engines to create and publish numerous video games and graphical based applications. A game engine software enhances the speed of the development process by providing the developer with simplified data management, pre-defined components and the possibility to publish the result on different platforms (e.g. Windows, OS, Android, WebGL, etc.) (Seifert 2015).

It is worth mentioning that game engines are designed to be widely different and each game engine has its focus and weak spots. Despite the specific differences, the main components of a game engine software could be considered as follows:

- Render engine: Component to generate 2D or 3D graphics.
- Audio engine: Component to create, modify and output sound.
- Physics engine: Component to simulate relevant laws of physics, such as collision, forces, and impacts.

- Logic: The possibility to define the structure of the game, design the scene or create events. These could be commonly achieved with the implementation of algorithms and scripts.
- Data management: The possibility to contain digital assets (3D model, audio, video, script, etc.), to use digital assets during runtime and structure those after publishing.

3.5.2 Software Development Kit

A Software Development Kit (SDK) is a bundle of programming tools and libraries which helps developers to create a specific application. The integration of a SDK into a game engine not only allows the development of a VR application inside a game engine, but also assures the impeccable operation of the hardware devices and stability of the entire software environment (Fig.62).

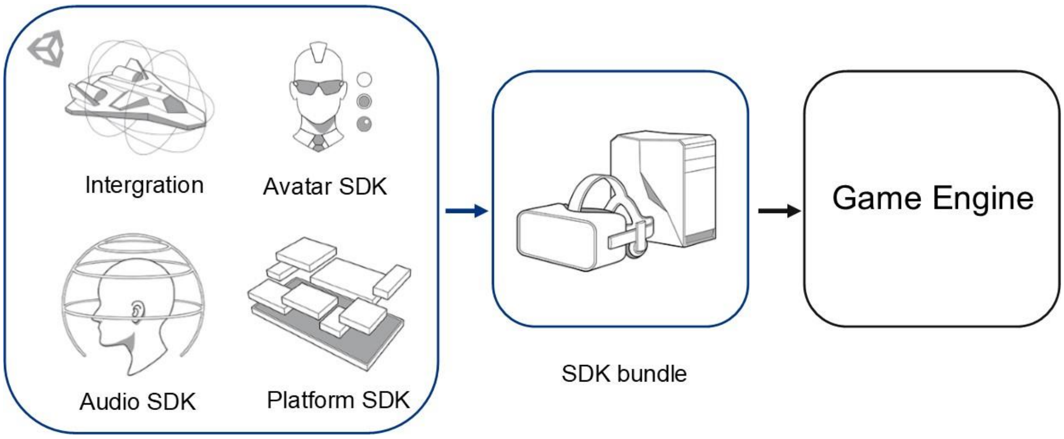


Figure 62. integration Oculus SDK into game engine

3.5.3 Digital assets

Like theatrical productions, many objects must be used on a stage or on a screen to create a convincing scene for the observer, and there is also no exception for VR development. After choosing a suitable VR hardware and setting up the VR development environment in the game engine, the last requirement for further development are the digital assets. Digital assets can be generally described as:

- Image files: textures, pictures or generally any 2D based images.

- Model files: geometry, shapes or any mesh-based model. Since game engines are primarily not a modeling program, all geometry related models should be imported into the game engine.
- Animations.
- Audio files: clips, sounds, and any acoustic based file.
- Scripts.

Digital assets form the content of the VR application: without digital assets, the VR application is only an empty space without any content or meaning. The content creation of an application is based on the placement of digital assets and defining special events of a scene.

3.5.4 Development of a VR application

Development of VR inside of a game engine consists of design, implementation, testing and publishing phases. A reliable VR application should have an interesting design, easy usability and hardware/software stability. Specifically speaking, the final VR application must contain the following factors:

- Content: What is inside this artificial world.
- Design: What is the story.
- Environment: How the physics behave and what the observer should see and perceive.
- User interface: How users control and navigate inside the virtual environment.
- Technical stability: Stability of digital communication between all the hardware devices of the VR system.

The final product of the development process is to publish an executable file from the game engine, which could be further launched on other computers independently. As a result, the user should be able to experience the VR environment with the help of hardware devices by executing the application on their own computer.

3.6 Virtual Reality application in architecture

3.6.1 VR as a design tool

Design process

With the application of VR, designers could "walk" inside the building before the construction work has been started. For example, an architecture office, named "CO architects" discovered this natural advantage of VR and use it to explore concept models in a fully immersive environment and actively integrate VR into their design process (@COarchitects) (Fig.63).

Figure 63. CO architects uses VR simultaneously with CAD as design method (@Architecturemagazine)

Design revision

VR is not only useful during the design stage, but also helpful during the design review phase. Since architects are often overwhelmed with their daily work schedules, to save time and improve efficiency, VR could also be applied as a team design review tool during/after the design phase. Specifically, architecture office Gensler hold a weekly so-called "VR-Jam" to gather the designers in a virtual environment to review their design (@Gensler) (Fig.64).

Figure 64. the weekly VR jam hold by Gensler as design revision(@Metropolis)

3.6.2 VR as a presentation tool

Often the project is complex and the customers are not trained, and do not have the time to study overcomplicated 2D documentation. With the application of VR, architects of the Jefferson High School modernization project actively used a VR station, as a presentation method to showcase the design and let school staff "walk" around in the virtual environment. As a result, customers fully understood the design and could perceive the 3D spaces entirely (@HMC Architects) (Fig.65).

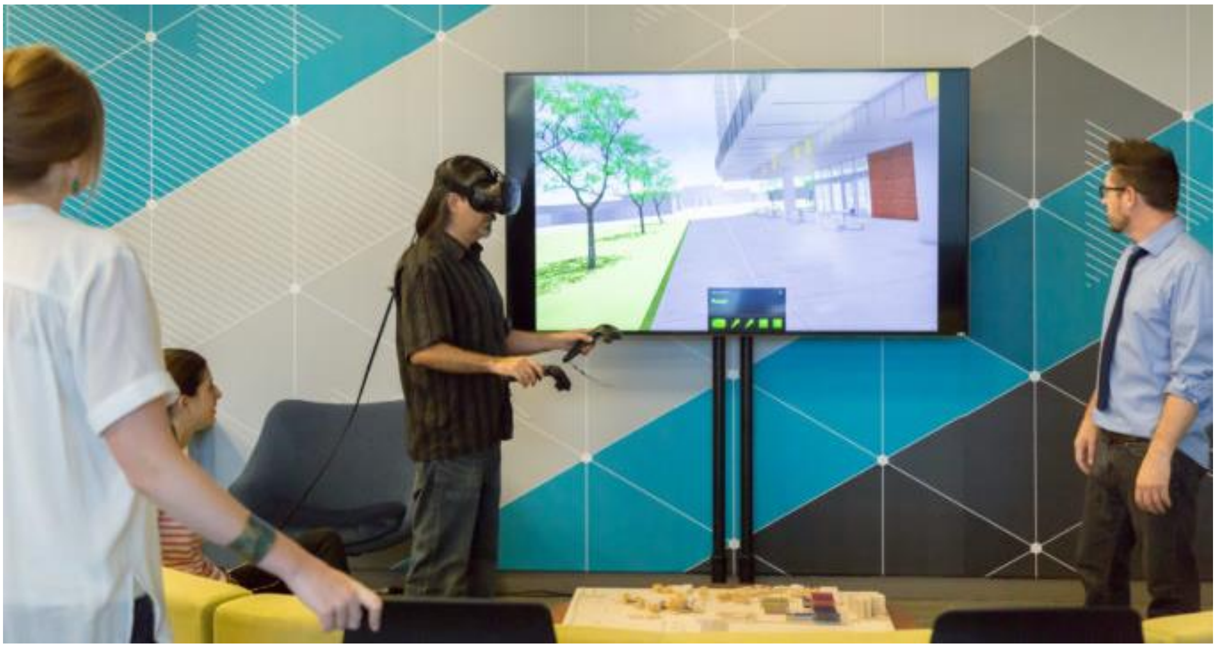


Figure 65. Jefferson High School modernization project, architects from HMC Architects applying VR as presentation method (@HMC Architects)

3.7 Advantages of virtual reality

Nowadays, with better accessibility, VR systems are no longer only tools used by professionals for research and training purposes; consumer-level VR systems can be easily purchased from every electronic market. VR systems have gained popularity with the boom in the VR entertainment industry: in the past years, numerous VR movies, apps and video games have been developed for consumer-level VR systems for entertainment purposes. This growing market and role shifting of VR enhanced the development of VR systems in a positive way, which made the prices of VR systems way more affordable for the public. In other words, architects now also have the possibility to experience VR technology and try to make use of it. Since VR gives the possibility to review the product in a low or no-cost way in a virtual environment, it is already widely implemented and used in different design disciplines. Specifically, various architecture-related disciplines such as exhibition designers, interior designers, kitchen designers and also architects have started to review and edit their designs in the VR environment.

From the technical aspect, the fundamental differences and outstanding advantages of VR based design compared with 2D based design are:

- Sense of own **presence**
- Sense of **space**
- Sense of **time** and **Action**

With its practical application in the architectural domain, VR could improve the current workflow through:

- At true 3D design environment with 1:1 scale.
- Saving time and cost
- Better communication

With these unique properties, VR-based design and presentation techniques outperform 2D-based design methods and allow the designer to perfect their design in an artificial environment. In the architectural domain, computer scientists are also developing widely different tools and software allowing architects to perform their design or review their design in a VR environment. It is also thinkable that in the near future, VR could become the standard design and presentation method.

CHAPTER 4

Integrating photogrammetric and VR workflow into the redevelopment process

The practical part of this thesis is to investigate the feasibility of integration of photogrammetry and VR in a real-world workflow. To achieve this, different use cases are applied to evaluate the workflow for selected **existing indoor situations**, **furnishing** and **materials**. Moreover, a **virtual reality application** is developed as an architectural design and presentation tool. It is important to mention that the focus of the practical part is to demonstrate the adapted workflow of architectural design, not the architectural design of examples themselves.

4.1 Use cases

4.1.1 Use case: indoor situations

To evaluate the real-world capability and feasibility of photogrammetry as a scan method for existing contexts, four different indoor situations inside a historical building from Eisenstadt have been selected as test scenarios for performing interior photogrammetry.

The historical city centre of Eisenstadt has an extensive amount of historical buildings which can be traced back to the Middle Ages. The historical building selected for this thesis is situated in Pfarrgasse 16, which is located in the historical city centre and surrounded by several famous historical sites (Fig.66)

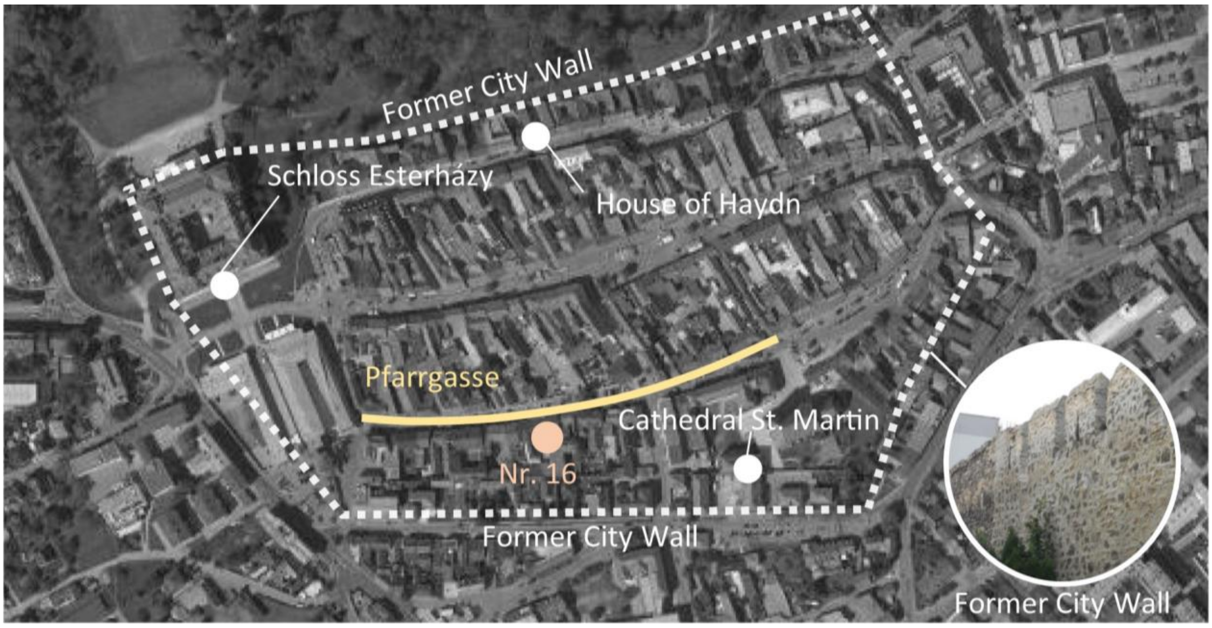


Figure 66. historical city centre of Eisenstadt

This building is not only representative of the typical historical city houses of Eisenstadt which date back to the 17th century, part of the building was also docked at the former city wall of Eisenstadt, which was demolished during the 19th. century. Unfortunately, due to certain financial reasons, the building was in an unpleasant physical condition and part of it was even threatened with demolition. Even though the building in Pfarrgasse is not protected by the heritage protection law, its artistic, cultural, and historical value is precious, and its loss could be irreversible. To prevent the loss, a local architect in Eisenstadt successfully professionally redeveloped the entire building in 2008. The carefully planned revitalization only used traditional lime plaster and local historical building materials. The renovation turned this almost endangered historical building into a modern historical building with 500 m² effective area, which is used for commercial and residential purposes.

For this thesis, four indoor situations inside this building have been selected due to their different physical conditions and uniqueness. These situations are: a vacant basement; a vacant rooftop; a renovated, vacant apartment; and a gallery (Fig.67 - Fig.68). These situations present themselves as typical existing contexts in a redevelopment process:

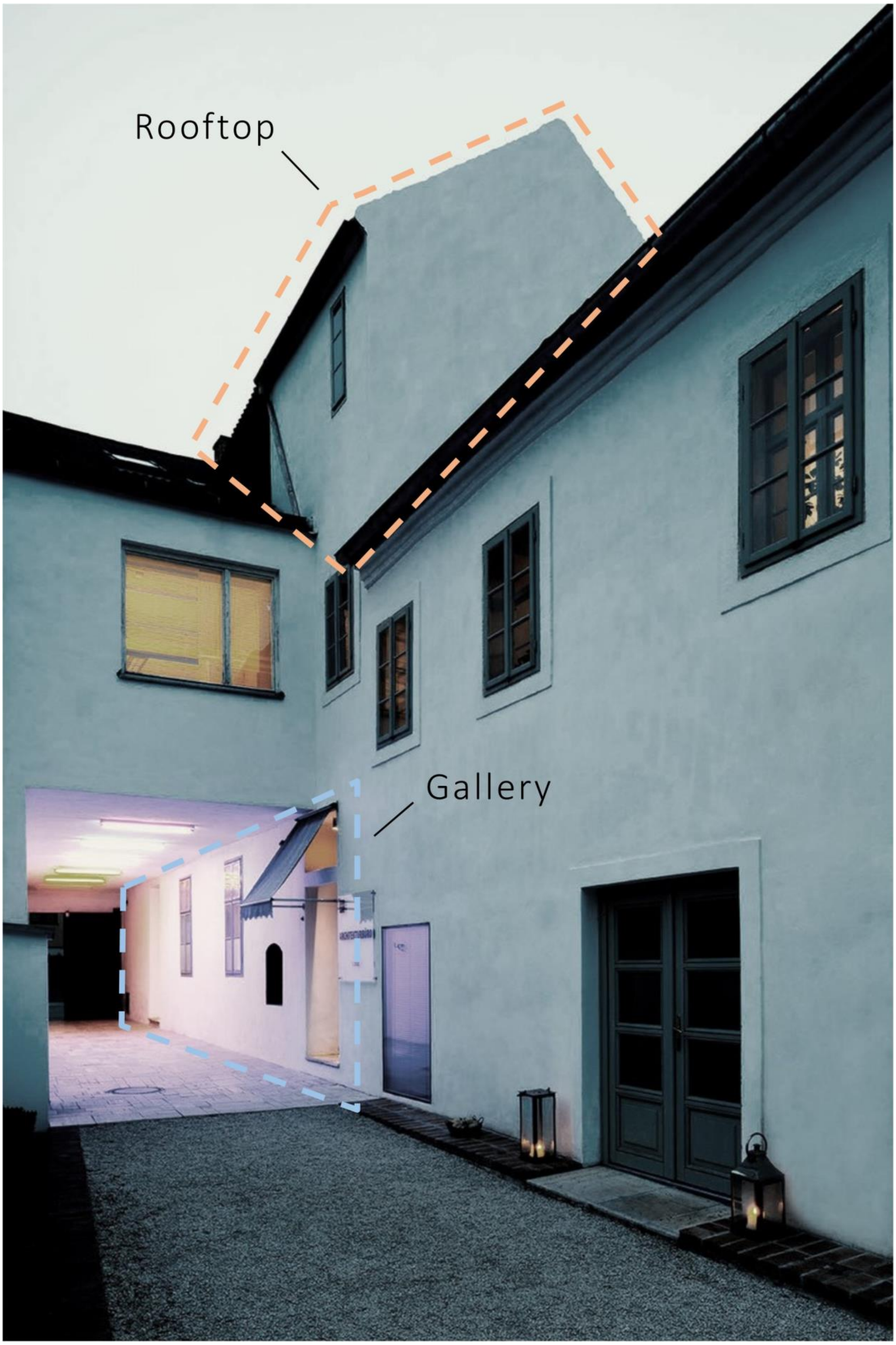


Figure 67. locations of the indoor situations: picture taken from the inner yard.

Figure 68. locations of indoor situations: street view of the house and picture of inner yard.

Basement

With the rapidly increasing demand for residential and work places in urban areas, redevelopment of vacant souterrain spaces for personal and commercial uses is gaining importance in architectural work. To create new available spaces for urban areas, architects are often tasked with redeveloping vacant souterrain spaces into reliable architectural space. In this sense, the vacant basement of the house was chosen as the first shooting situation. It should represent the typical basement redevelopment situation of the existing context.

The technical challenge of photogrammetry application in this location was the lighting, since it has only a very limited light source to provide capable images. Moreover, the details of wall surfaces (mixed historical construction of stones and bricks and wet spots) should be kept after the photogrammetric reconstruction, so that the technical planners and architects could possibly review the photogrammetric result as the “site inspection”, and make further decisions based on the photogrammetric reconstruction (Fig.69).

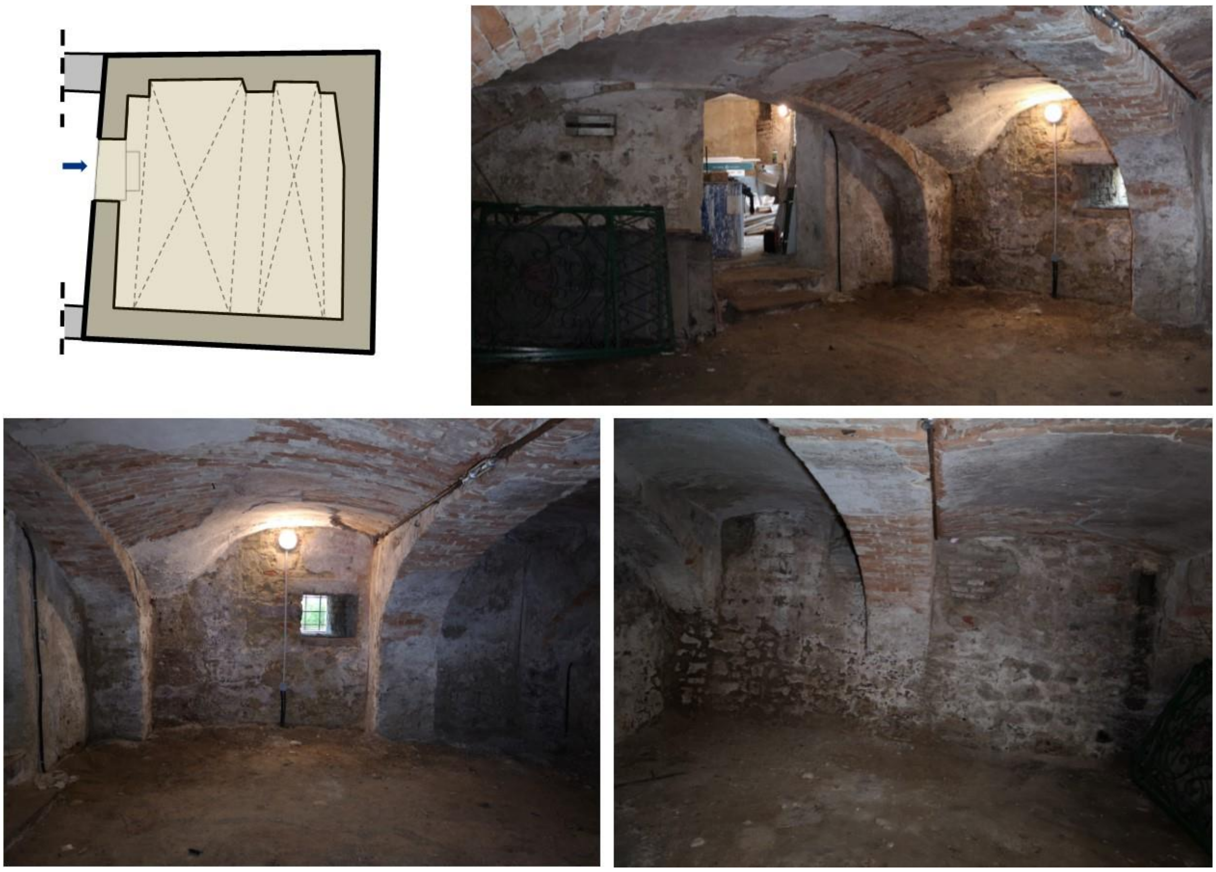


Figure 69. situation 1: basement

Rooftop

High demand for spaces also leads to increased redevelopment of vacant roof areas. Development of vacant roof space into residential or work space has become one of the most typical architectural works nowadays. In contrast to vacant souterrain spaces, roof areas are mostly lightweight constructions which consist of numerous constructional elements and joints, which need especially detailed documentation.

Accordingly, the vacant rooftop of the house was chosen as the second shooting situation. The technical difficulty of this room is to record the complex construction structure of this rooftop (Fig.70): as the numerous different wooden structures of the rooftop intersect and overlap with one another, the photogrammetric reconstruction should preserve all the details about the geometry, conditions, and connections regarding the wooden structures of the rooftop.

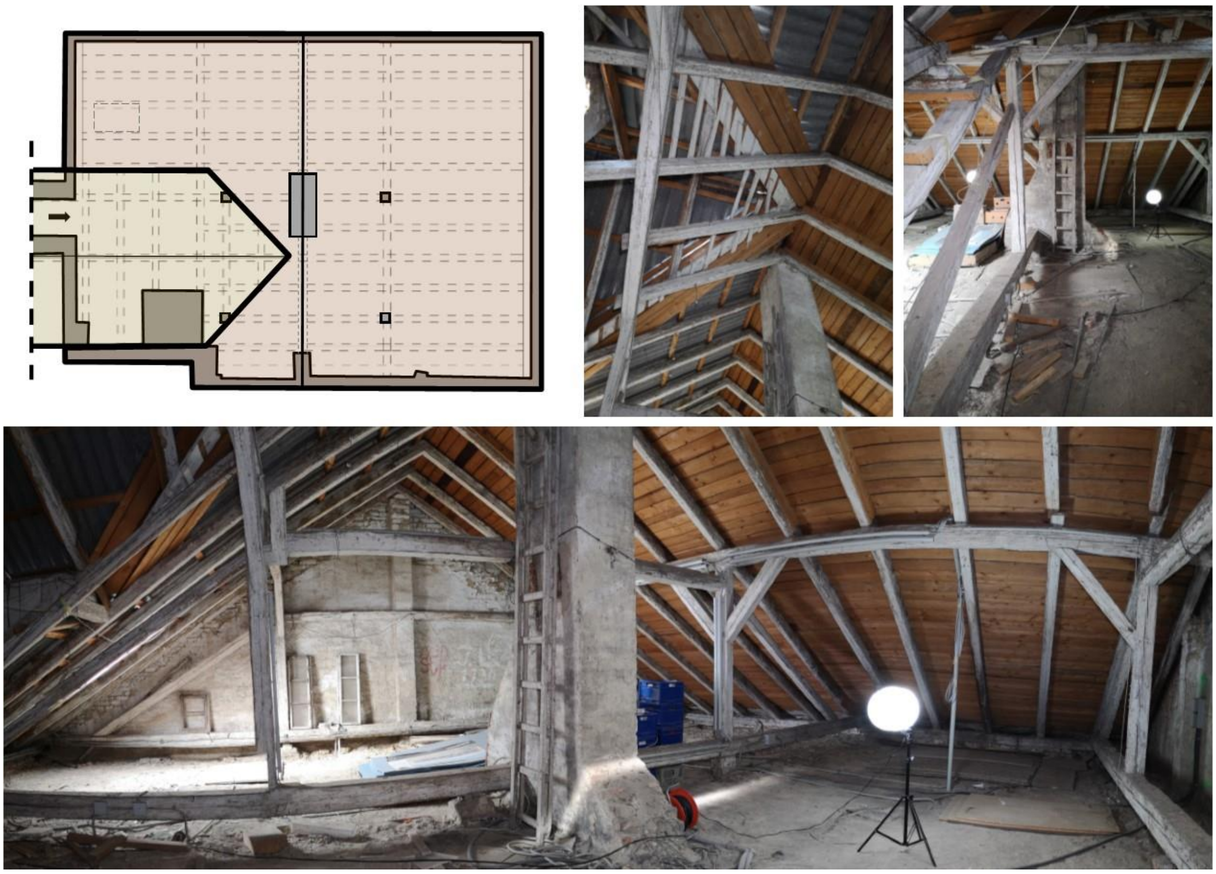


Figure 70. situation 2: Rooftop

Apartment

The apartment is on the first floor of the building and was first renovated in 2008. The most interesting part of the apartment is that it is directly docked on the historical city wall of Eisenstadt, which has particular historical value in being kept. Accordingly, the historical wall is intentionally kept visible as an architectural design idea (Fig.71).

Renovation of residential premises is a common topic of redevelopment. Since residential spaces mostly consist of large wall surfaces with less features, it is necessary to investigate the technical capability of photogrammetry in this given scenario. Specifically, the surfaces of walls, ceilings and the kitchen could be critical for photogrammetric reconstruction. However, photogrammetric reconstruction should still be adequate enough for architects and technical planners to make further decisions and planning. In this apartment, the interesting detail (historical city wall of Eisenstadt) as the existing context should also be kept after the photogrammetric reconstruction.

Figure 71. situation 3: apartment

Gallery

The gallery “ArchitekturRaum Burgenland” is located on the first floor towards to the street, and is primarily used for architectural exhibitions: it is also a local platform where architects and architecture-interested parties to hold events and exchange ideas regularly. Therefore, the gallery has been completely freshly renovated, painted, and furnished.

The gallery is chosen to investigate the technical capability of photogrammetry: In other words, the existing physical condition of the gallery is not ideal for photogrammetric measurement in any sense; in contrast to other scenarios, the gallery has large sized window areas with a continuously changing background (moving people and cars on the street), moreover, the surfaces of the gallery (floor, wall and ceiling) are primarily painted white (Fig.72) and are highly reflective. The interesting aspect of this location is to study if photogrammetric reconstruction software is capable of reconstructing the geometry correctly.

Figure 72. situation 4: gallery

4.1.2 Use case: furniture scan

During the redevelopment process, architects could be tasked with keeping certain objects (e.g. furniture) or materials and including these into the redevelopment design. This means architects require digital versions of these objects and materials (digital assets) for the further digital workflow (CAD, Rendering).

Moreover, digital assets also are one of the most important components for setting up the VR scene inside the virtual environment. Fortunately, various non-specific digital assets can be downloaded from widely different websites or platforms on the internet, the most popular sources (e.g. “BIM Object” (@BIMObject) or “Unity-assets store” (@Unity)) offer a variety of digital assets such as 3D models, textures and materials, which could be easily used for scene creation. However, obtaining digital assets only relying on this method has several disadvantages:

- Cost: often digital assets are made by 3D artists commercially and developers must pay a certain amount of money to obtain them. Due to the fact that a VR scene often requires numerous objects, the cost of digital assets in total could be enormous. In other words, this is not a practical way for architects to obtain digital assets.
- Limitation of free digital assets: fortunately, numerous free versions of digital assets can be also obtained from the internet. These cost-free digital assets could be used without consideration for costs and copyright issues, however, their variety and quality are often limited.
- Unspecified digital assets: during architectural digital work, very specific digital objects (e. g. a specific type of flooring or piece of furniture) are required. Even though the variety of digital assets is immense, it is still demanding to find specific digital objects from online sources for digital architectural work.

To extend the availability of design possibilities for architects, it is advantageous to create digital assets on one’s own. The most time-consuming part of 3D model creation is to model an existing object without a template. In practice, modeling in digital drawing software is the most common method to re-create a 3D model, however, the modelling process often takes a long time due to the complexity and quality of the 3D model. Fortunately, with the application of photogrammetry, it is possible to obtain textured 3D models of different existing objects without extra effort. To investigate the feasibility, three pieces of furniture with a unique design will be scanned with the application of exterior photogrammetry (Fig.73).

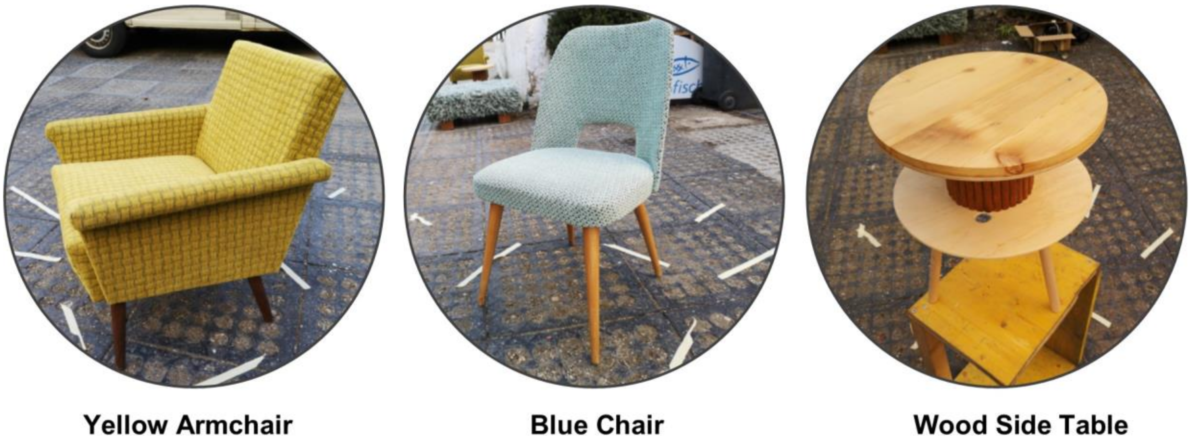


Figure 73. use case: furniture scan, three pieces of furniture, furniture are provided by Miststück (@Miststück)

4.1.3 Use case: material scan

During the redevelopment process, based on the wishes of customers or for other reasons, specific existing materials (e.g. flooring, textile) should be kept and used in the redevelopment project. Therefore, it is helpful and necessary for architects to create their own digital material to study the design with the specific material applied. In this use case, serval selected physical materials (Fig.74) will be scanned with the application of micro photogrammetry to create digital materials.

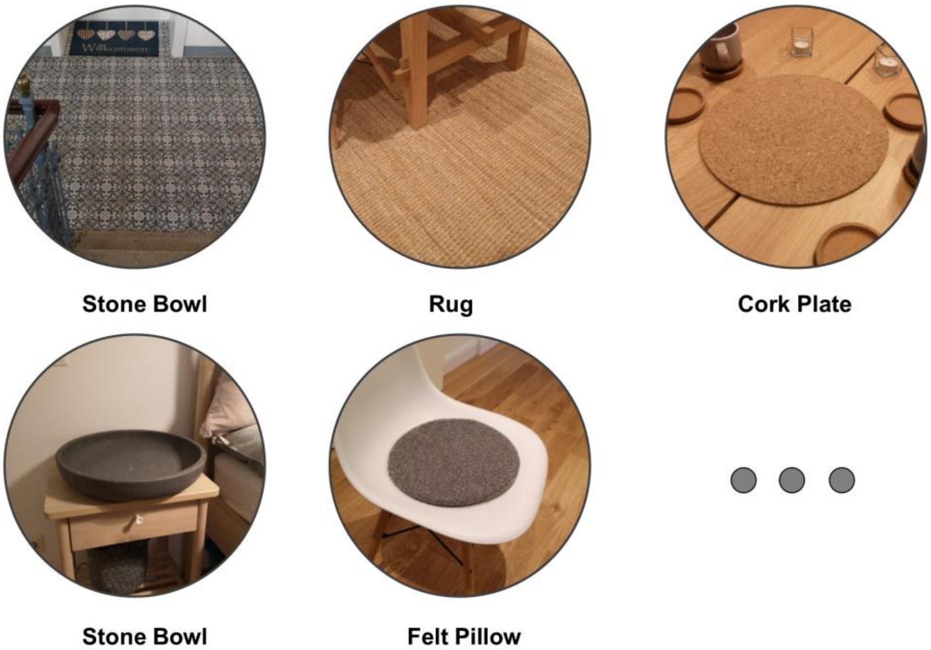


Figure 74. use case: material scan, selection of physical materials

4.2 Integration of the photogrammetric workflow into the redevelopment process

The goal of this subchapter is to investigate the feasibility of the application of photogrammetry with consumer-level equipment in different shooting situations. In other words, if and how architects could perform photogrammetric scans successfully without expensive equipment for different purposes. Moreover, the scan results (interior scan, furnishing scan, material scan) will be integrated into the redevelopment process to accomplish an adapted version of a redevelopment workflow (Fig.75).

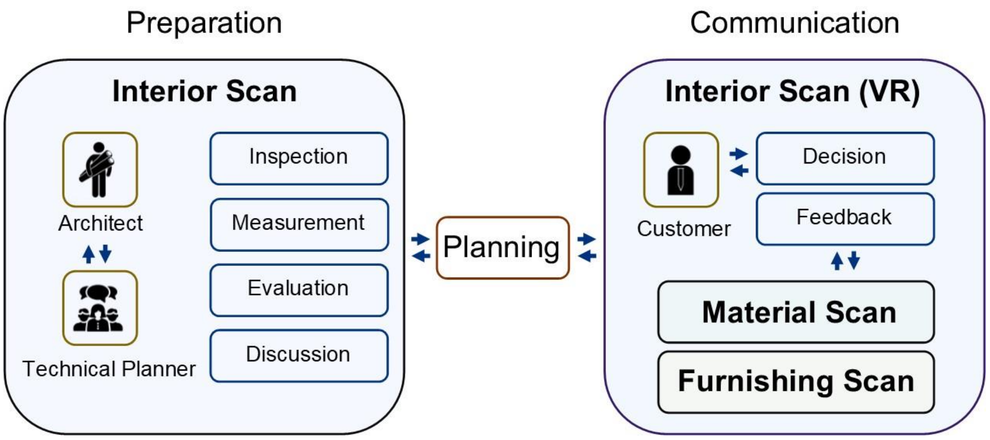


Figure 75. integration of the photogrammetric workflow into the redevelopment process

In the first topic, four different indoor scenarios: a basement, a rooftop, a apartment and a gallery will be scanned with the application of interior photogrammetry. In the second topic, pieces of furniture will be scanned with exterior photogrammetry. In the last topic of this subchapter, different materials will be scanned using a self-made material scanner. (Fig.76)

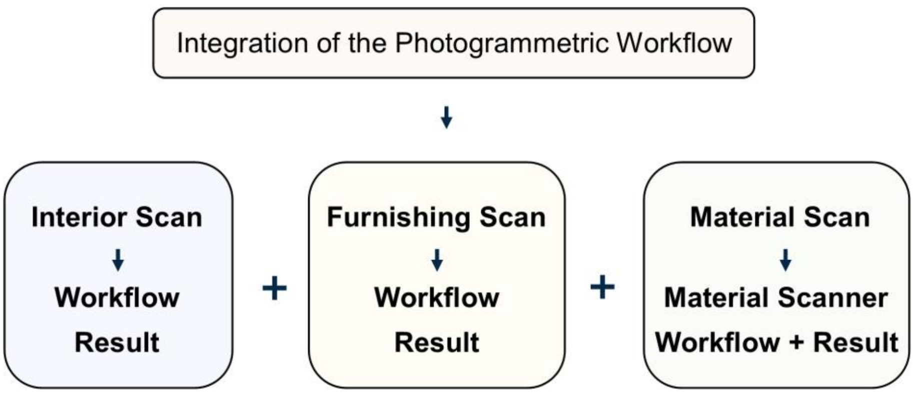


Figure 76. content structure of subchapter 4.2

4.2.1 Interior scan

4.2.1.1 Workflow of the interior photogrammetry application

Data acquisition

Equipment:

To demonstrate the simplicity of photogrammetry application for architects, only the most basic equipment is used intentionally in this thesis. Specifically, instead of using a DSLR camera, a smartphone camera (Huawei P20 Pro) will be used in this thesis. To improve the image quality for a better final reconstruction result, other additional basic photography tools are also used (Fig.77):

- Tripod: stabilize the device during image gathering, reduce noise and artifacts of images.
- Additional lighting: compensate for the lack of lighting to improve the amount of light which could be gathered by the sensor.
- Remote trigger: remote trigger or taking photos remotely without physically touching the camera device could avoid internal vibration of camera devices, thus could avoid noisy and blurry images.

Figure 77. equipment of photogrammetry scan: smartphone Huawei p20 pro, laptop (Lenovo P50), tripod and studio light with stand

Strategy:

Since these shooting locations are different, specific camera movement pattern must be applied to each room to gather capable loops of images (Fig.78).

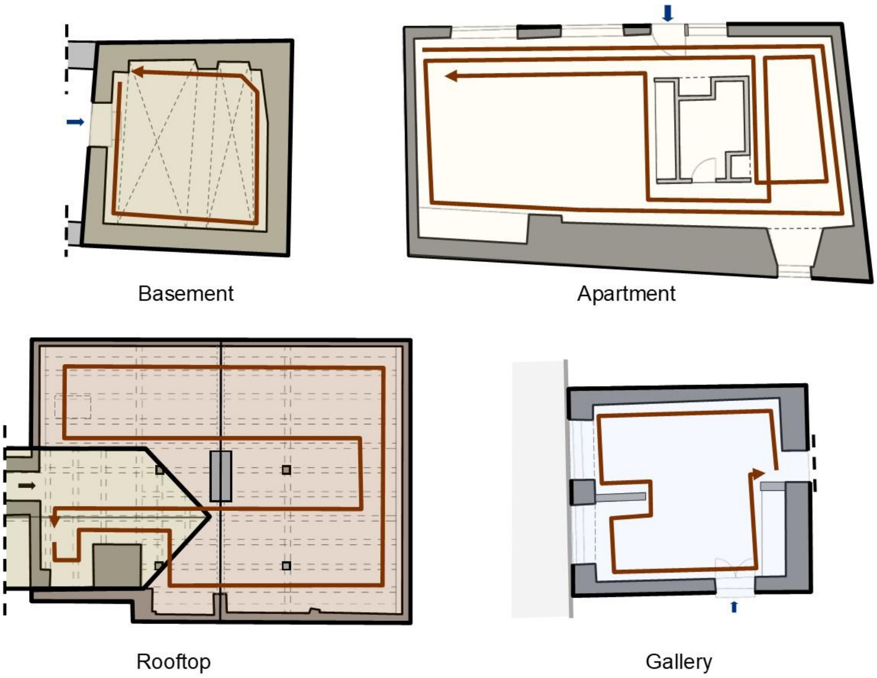


Figure 78. schematic demonstration of camera movement pattern on-site

Images acquired:

As a result, loops of pictures with ~ 80 % overlapping areas could be gathered from each of these rooms (Fig.79).

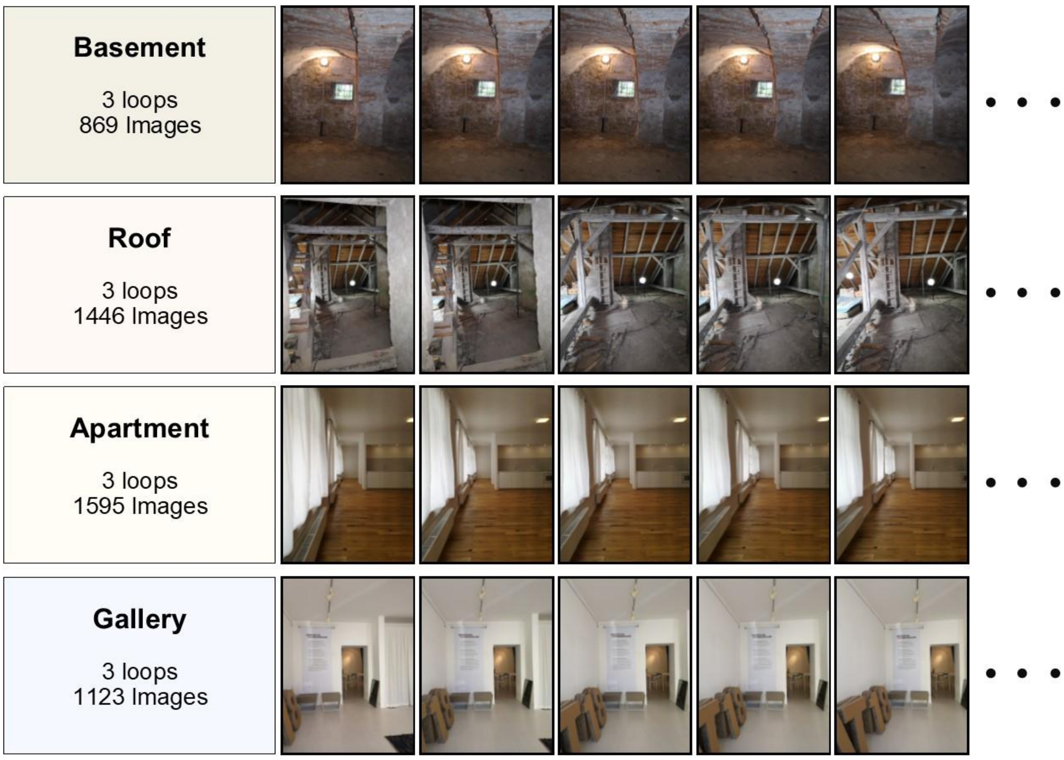


Figure 79. images acquired on-site

Reconstruction

For the digital reconstruction process, the photogrammetry software “Reality Capture” (@Capturing Reality) was used in this thesis: Reality Capture particularly with its inexpensive abonnement price policy, simplified user interface and faster reconstruction speed, allow users to obtain results in a single automated workflow.

Image analyses and camera alignment:

With the integrated “Alignment” function of Reality Capture, the imported images could be analysed, and numerous feature points could be detected automatically, moreover, the camera positions from the on-site shoot could also be determinated by the software. As a result, about 90% of the pictures taken on-site could be recognized and re-aligned by the software (Fig.80).

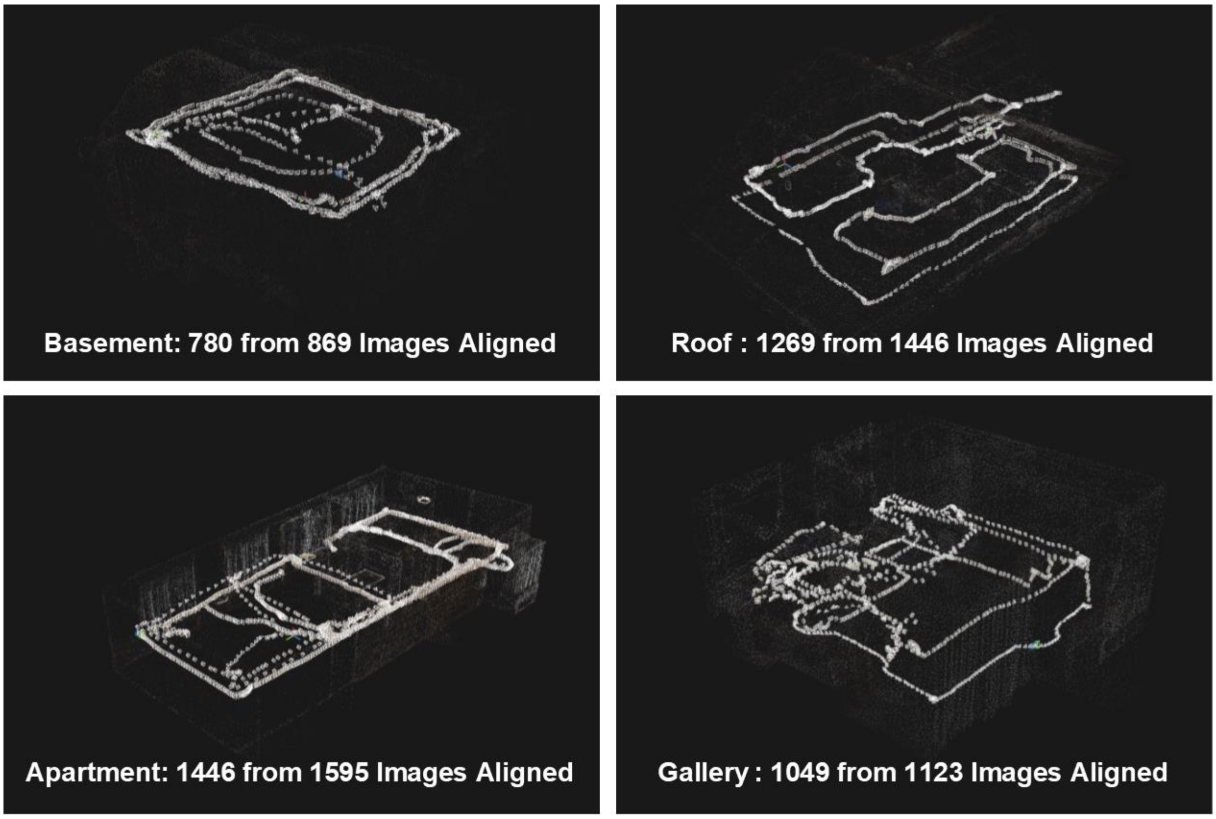


Figure 80. camera alignment in Reality Capture

Point cloud generation and meshing:

With the function called “Calculate Model”, point cloud and mesh geometry can be generated at the same time. The initial point cloud and the mesh geometry generated from the basement and roof are dense (over 60 million vertices), which is the indicator for a reliable reconstruction, but not practical for the further process, in this sense, these are reduced with the function “Simplify Tool” to a lower dense version of models

(Fig.81). However, on the other hand, the models generated from the apartment and gallery both have low vertices counts, which causes artifacts and incomplete reconstruction areas ("holes") in the 3D meshed models. Especially critical is the 3D model reconstructed from the gallery, which has numerous missing geometry due to the large window areas and very flat monotonous surface properties of the gallery itself (Fig.82).

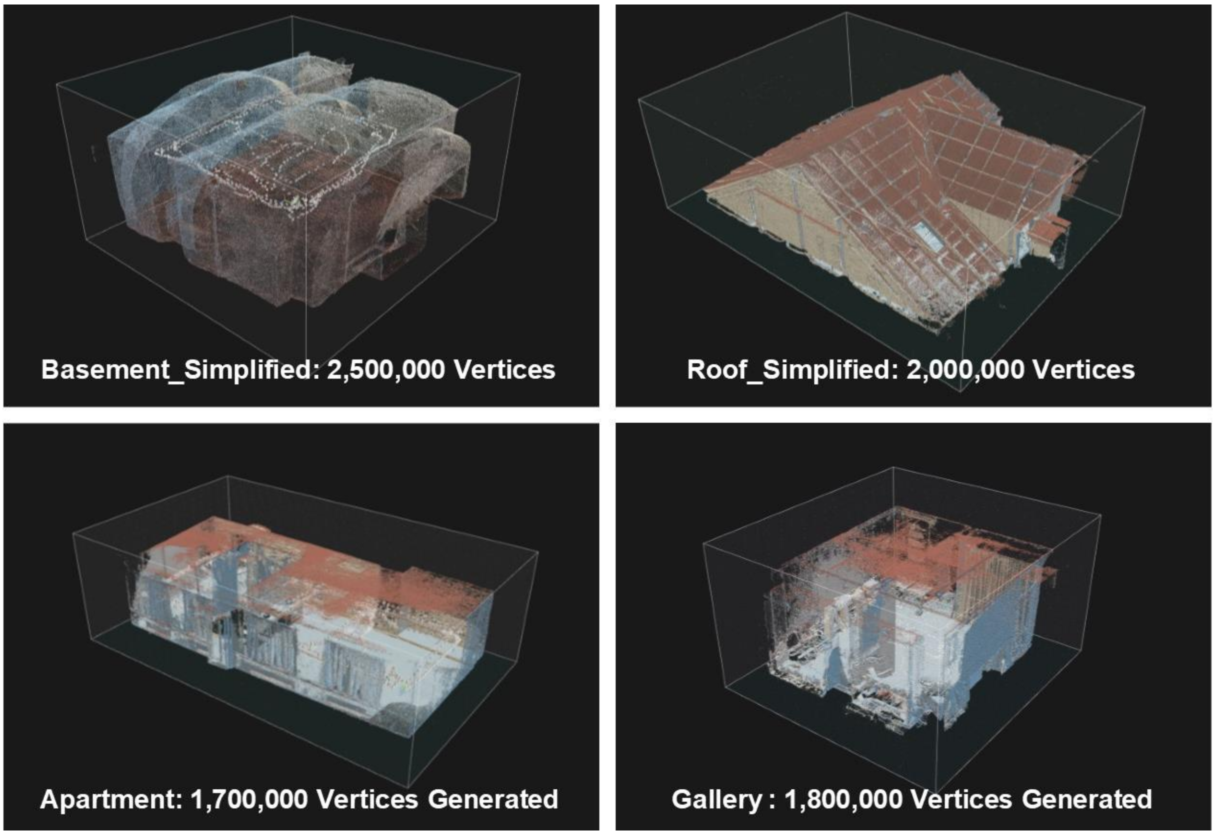


Figure 81. point cloud and mesh generation in Reality Capture

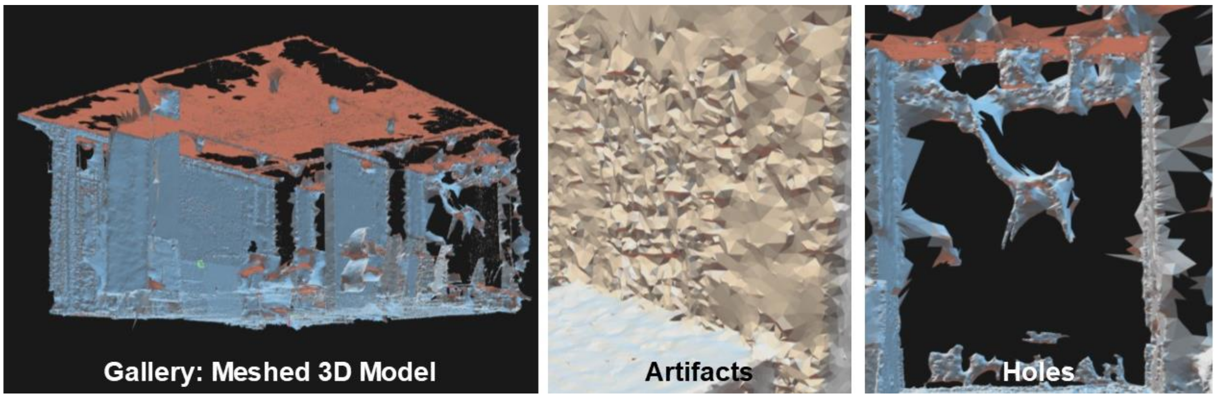


Figure 82. incomplete reconstruction of the gallery

Texturing:

As the final step of the reconstruction process, previously generated 3D models from four scenarios could be textured with the original picture taken on-site (Fig.83-Fig.84).

Figure 83. textured 3D models of basement and roof

Figure 84. textured 3D models of apartment and gallery

However, the photogrammetric reconstruction of the gallery has numerous geometric artefacts which cause serious problems with the final result. Specifically, due to the lack of surface features and continuously moving background, the window areas, glazing surfaces and large white painted wall and ceiling could not be correctly geometrically reconstructed and textured (Fig.85).

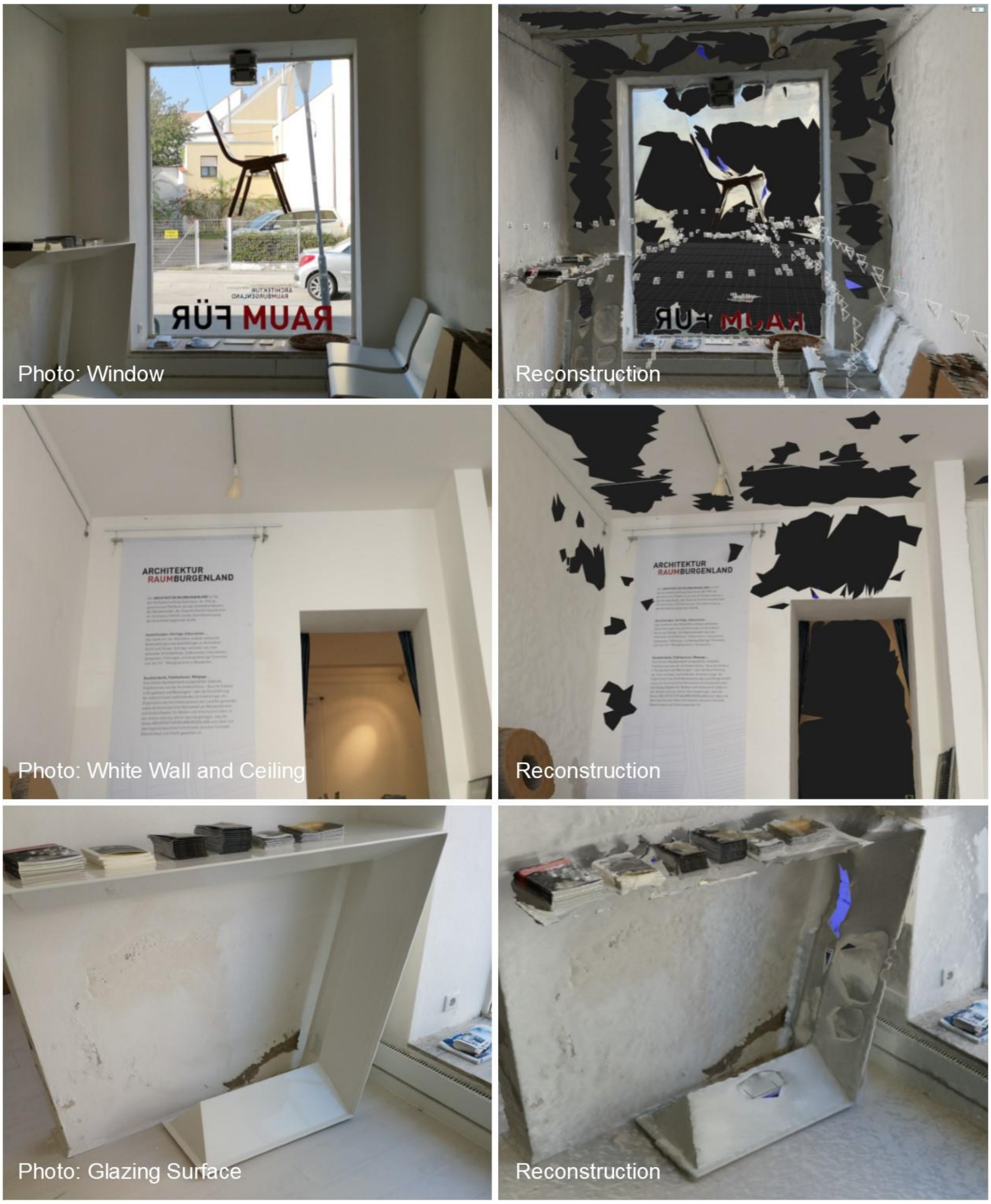


Figure 85. comparison of real on-site photo and photogrammetric reconstruction of the gallery

Post processing

Target platform and render performance:

The results of the previous reconstruction process could now be to be exported as textured models into diverse platforms as visualizations for widely different uses:

- Export as 2D format: rectified views, plans.
- Export into analytic tools: structure or static analysis.
- Export into CAD platform: 3D geometric reviewing and drawing.
- Export into render platform: static rendering.
- Export into virtual reality: digital interactable, editable, real-time 3D reality.

In practices, it is essential to reduce the number of meshes (Triangles) to a level which is more compatible with software and hardware (Magnor 2015). Regardless of which target form is desired, there are generally two key factors that directly impact the visualization performance (render performance) (Akenine-Möller 2018):

- Computing power: Determined by different hardware system-units such as graphics process unit (GPU), central processing unit (CPU), random-access memory (RAM) and hard disc.
- The number of elements that must be rendered: Numbers of geometries (complexity of geometry), textures, lighting, physics, animation, audio, effect, etc.

It is essential to understand the impact of computing power and the number of render elements on performance. One indicator of performance is how many pixels a computer must generate on-screen per second; if the computing power is low and the number of render elements is high, fewer pixels can be generated on screen per second, and vice versa, if the computing power is high and the number of render elements is low, more pixels can be generated on screen per second.

For a traditional representation method like a monitor, which has a lower resolution (high definition: 1920x1080 pixels), it is acceptable to watch images on the screen at ~24 frames per second (FPS); broadly speaking: ~ only 50 million pixels must be generated on the screen each second. In other words, it is possible to directly apply the non-simplified photogrammetric result.

However, a target platform like a VR system, which uses a HMD (head mounted display) as display, has two 1400x1600-pixel displays (HTC Vive Pro) with a desired 90 frames per second for the immersive experience; the computer must generate ~400 million pixels in total per second, this means a VR platform requires multiple times the computing power of a traditional 2D monitor as display method. In other words, in the VR environment, it is essential to reduce the render elements to compensate for computing power. Therefore, the number of geometries (triangles) must be further reduced.

Mesh repair and decimation:
In the practice, several applications could be used to repair or decimate a mesh. In this thesis, mesh edition tool "Z-Brush" (@Pixologic) was used, since it could handle large, complex geometry without performance issues. With integrated mesh edition tools inside the software, such as: Smooth and Close Holes, artifacts on the mesh surfaces from the reconstruction process could be edited and smoothed out or reconstructed entirely. Moreover, the number of triangles of the geometry could be reduced to an exact number by the software.

Textured baking:
With the help of "Substance Painter" (@Adobe), the required texture maps for a VR (Unity) environment could be generated from the software to give simplified meshes a highly detailed visual appearance (Fig.86).

Figure 86. baked texture maps of basement: on the left: high resolution mesh of basement, on the right: low resolution mesh with 50,000 triangles and texture maps.

4.2.1.2 Result of the interior photogrammetry application

As a result of the whole interior photogrammetric workflow, all four shooting scenarios were able to be scanned and reconstructed (Fig.87). However, due to the large missing areas of the result from the gallery, none of the repair procedures could bring the scan result of the gallery to a capable state. Therefore, the gallery will not be considered as a successful scan.

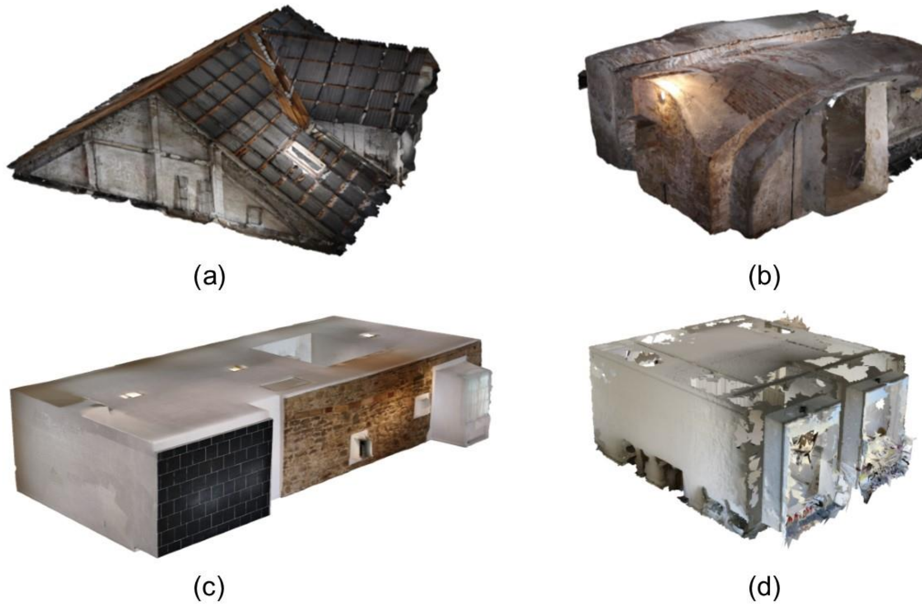


Figure 87. 3D model of scan result (a). rooftop (b). basement (c). apartment (d). gallery

Based on the computing power of the computer, the time needed to evaluate of photogrammetric data varies greatly. Since the reconstruction process is highly automated, the human effort required for photogrammetric scans is relatively low (Fig.88).

Object	Preparation (min)	Image gathering (min)	Reconstruction (min)
Rooftop	~ 50	~ 60	~ 900
Basement	~ 30	~ 30	~ 480
Apartment	~ 20	~ 60	~ 600
Gallery	~ 0	~ 60	~ 300

Figure 88. time consumption (in minutes) of photogrammetry of three room in Eisenstadt, tables in blue represent human effort, green represent computer effort

However, the post-processing of the scan data into a VR-friendly version is still done manually, and this takes often multiple hours of additional work. Nevertheless, as the end result, the models of three indoor scenarios (rooftop, basement and apartment) could be post processed as a VR-friendly version (Fig.89 – Fig.91) which could be integrated into the VR environment.

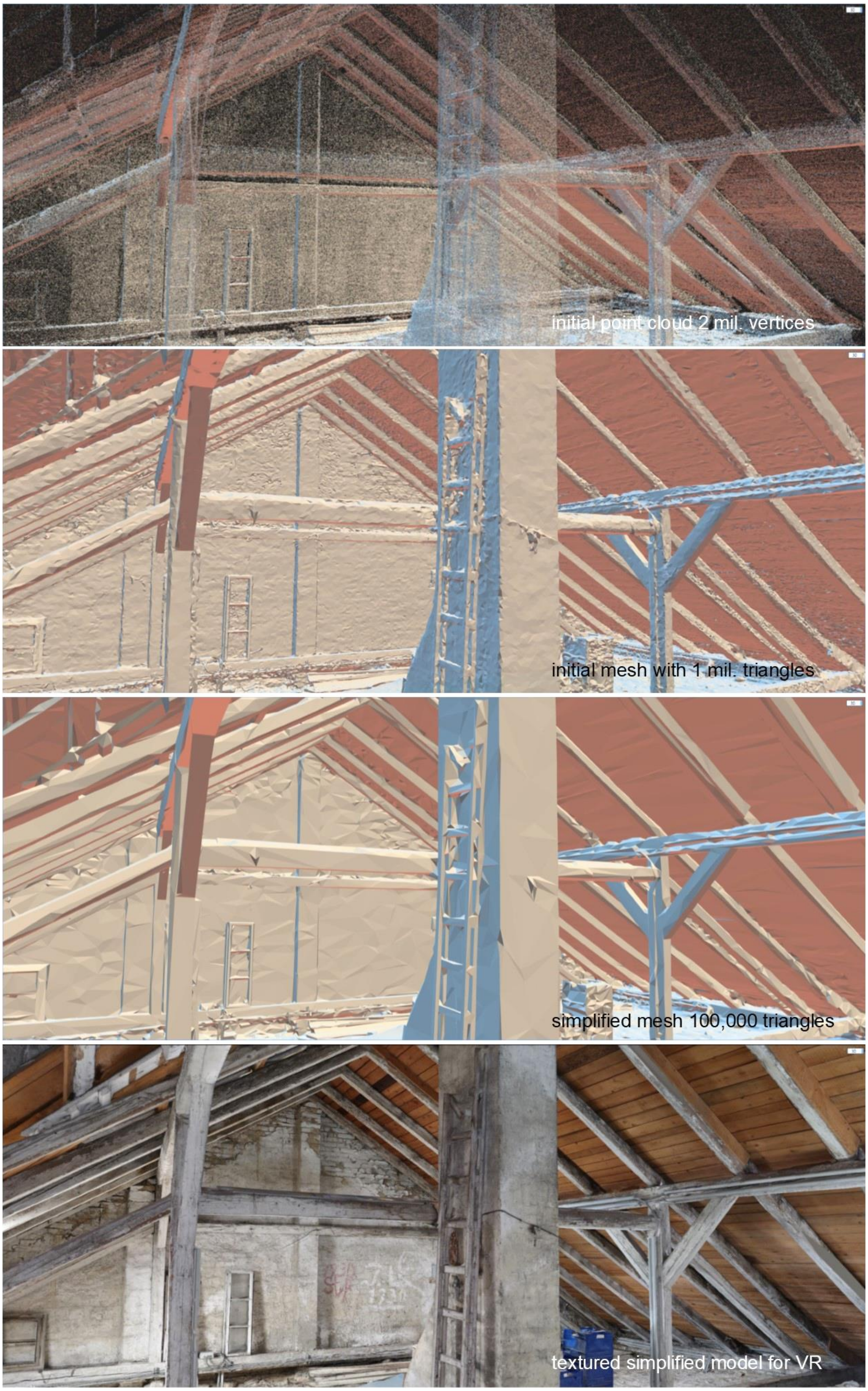


Figure 89. final model for VR integration, rooftop

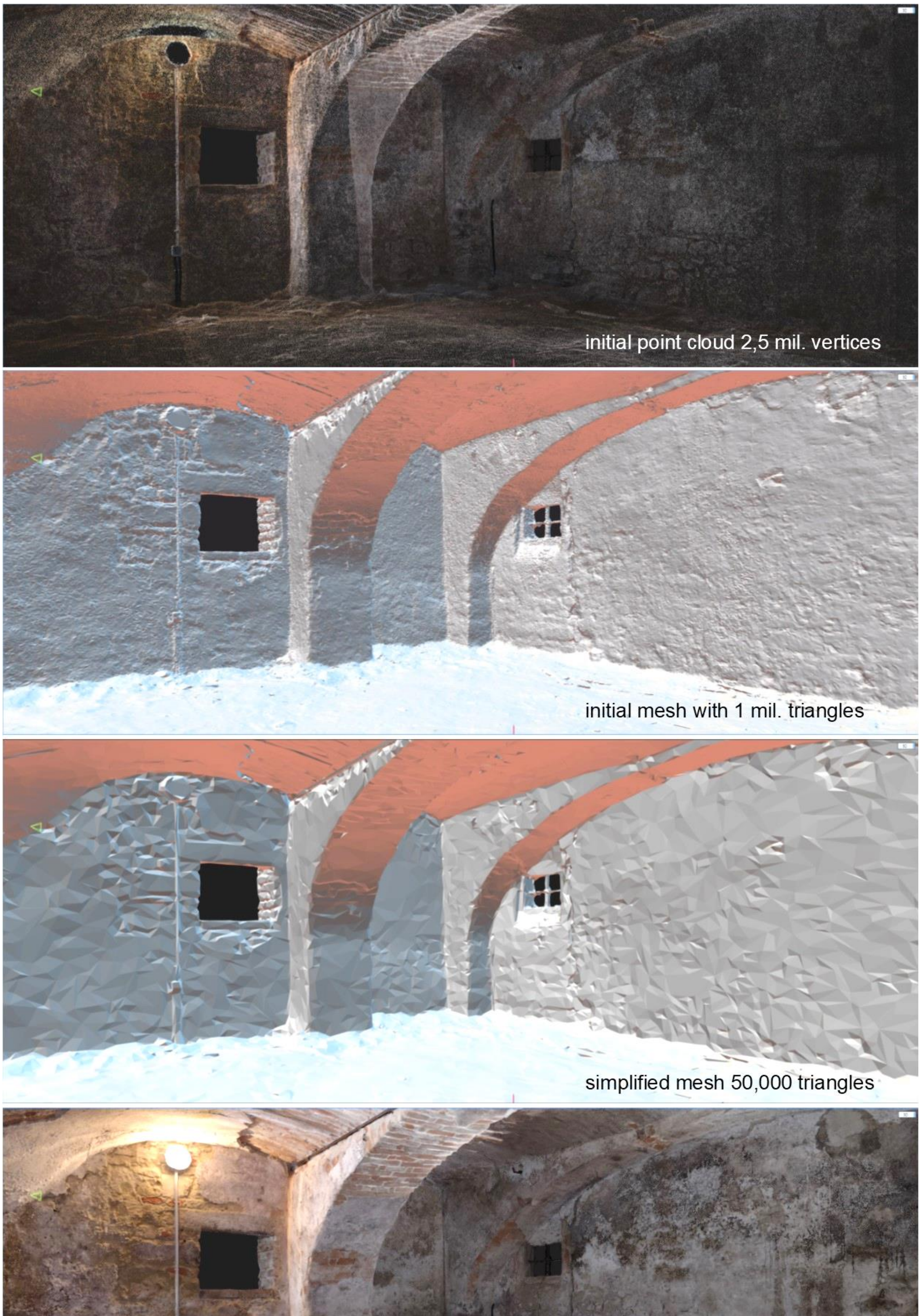


Figure 90. final model for VR integration, basement

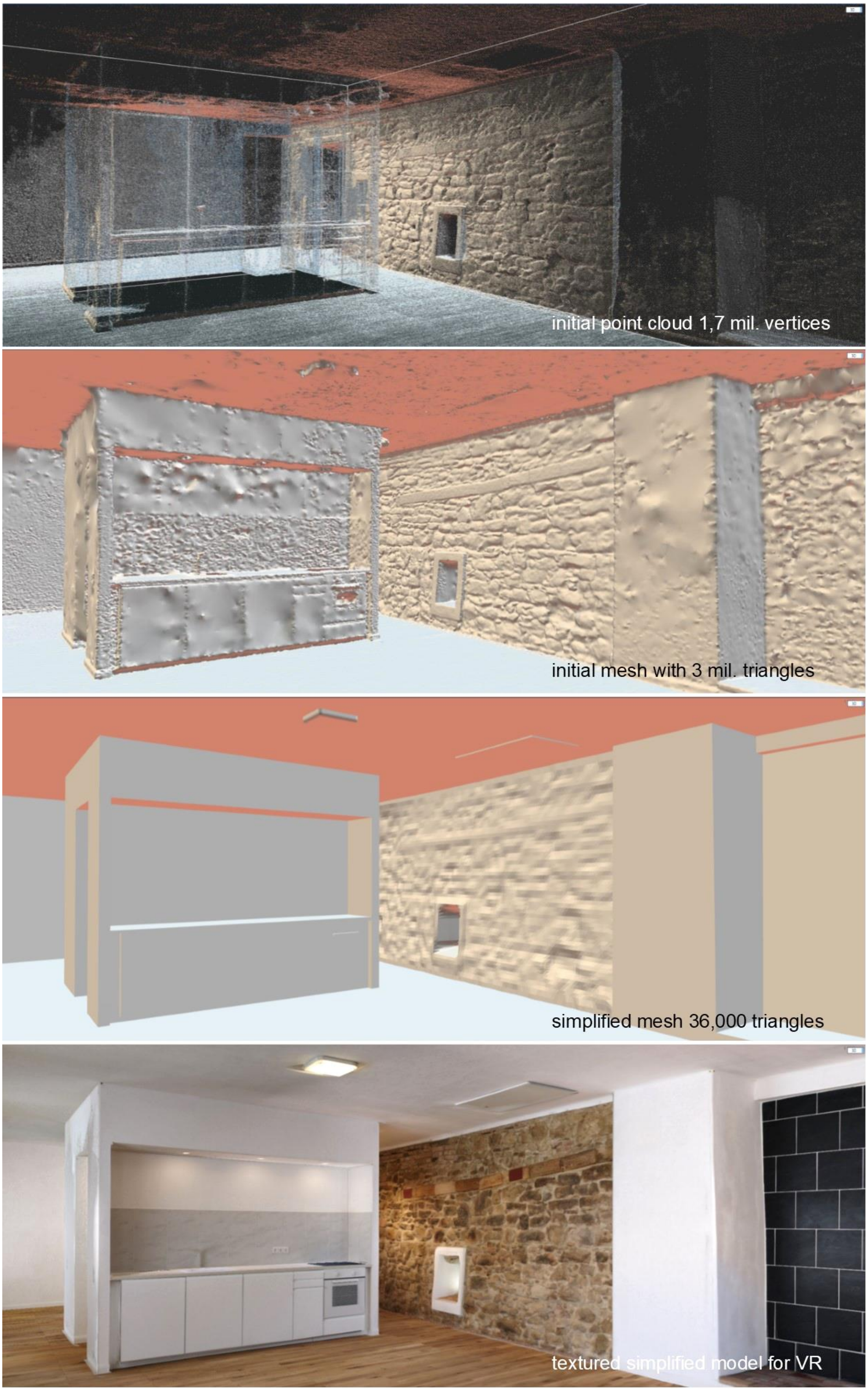


Figure 91. final model for VR integration, apartment

4.2.2 Furnishing scan

4.2.2.1 Workflow of the exterior photogrammetry application

Similar to the previous workflow of the photogrammetry application with four scenarios in Eisenstadt, in which the inner side was scanned (interior photogrammetry), in contrast, to obtain the outer side of objects, exterior photogrammetry will be applied to scan smaller objects. Specifically, the circular network shooting method is applied by gathering a loop of images with overlapping areas (Fig.92). Apart from that, the following photogrammetric workflow steps (reconstruction and post processing) remain the same as in the previous subchapter.

Figure 92. section of images of application of exterior photogrammetry, furniture provided by Miststück (@Miststück)

4.2.2.2 Result of the exterior photogrammetry application

Due to the lower number of images acquired and the much smaller scale of the objects, results could be obtained in under 2 hours (Fig.93). In this sense, applying photogrammetry scans to small objects allows architects to create their own 3D model (e.g. furniture, façade element, statue, etc.) as digital assets rapidly. This method is especially useful for fulfilling the purpose of an architectural VR application.

Figure 93. the results of photogrammetry scan from furniture pieces: 1. yellow armchair 2. blue chair 3. wood side table, furniture provided by Miststück (@Miststück)

4.2.3 Material scan

4.2.3.1 Material scanner

With the method mentioned in chapter 2.5.1.1, different types of material could also be scanned with the application of micro photogrammetry. However, this technique requires extraordinary lighting and position conditions, and tedious preparation and lighting setup must be done separately each time. Depending on the physical location and lighting conditions, it is often not possible to scan material at all (e.g. outside during the day, sunlight is always present so that correct lighting can not be set). To accelerate the material scan process, reduce inconsistency and to improve the final scan quality, a 3D printed self-designed material scanner (inspired by Dave Riganelli) (@ArtStation) is built in compliance with the technical principles (Fig.94).

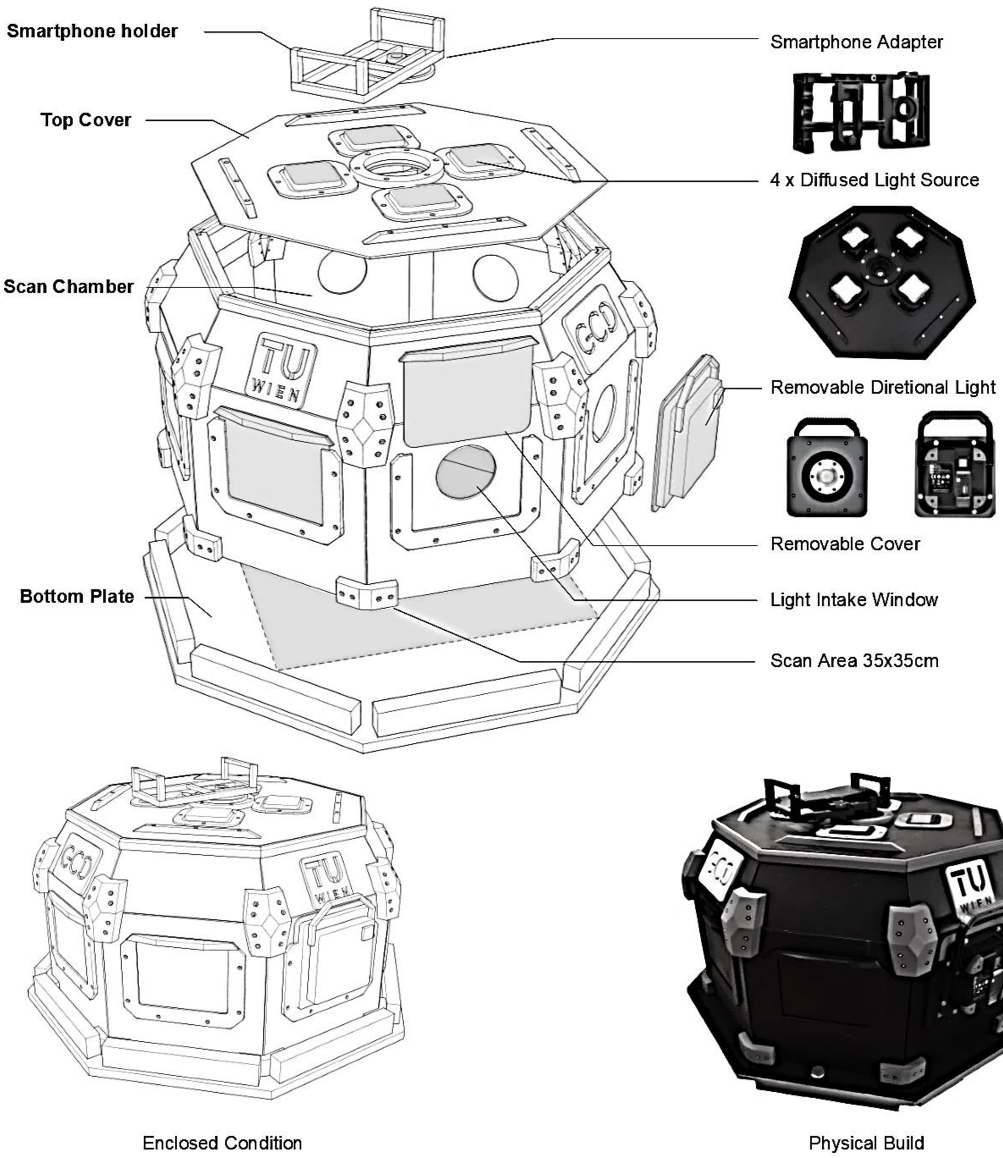


Figure 94. 3D printed material scanner

The scanner operates with full enclosure, it allows users (e.g. architects) to scan flat surfaces of the material under controlled lighting conditions with a photo device (e.g. smartphone) rapidly. It could be used to scan small scale material probes (e.g. architectural material probes, textiles) or used for scanning larger scale material (e.g. flooring, ground, tiles) (Fig.95).

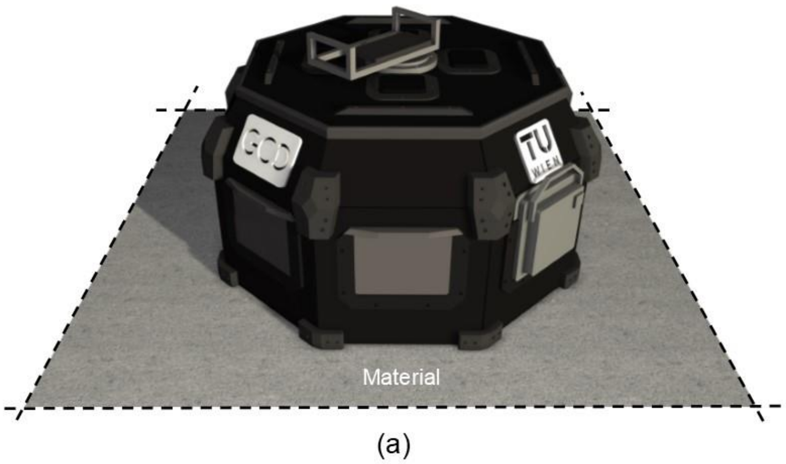


Figure 95. (a). scanning large scale material by placing scan on top of the target surface (b). scanning smaller material probe by placing the probe inside of the chamber

By placing a smartphone into the adapter, which could be further attached to the top cover of the scanner, static images from the material could be gathered. The removable LED directional light source and covers of light input windows allows users to change the position of the directional light to create 8 separate directional lighting conditions (Fig.96). Furthermore. with the removable top cover with 4 diffused LED light attached to it, one colour image without shadow could be gathered.

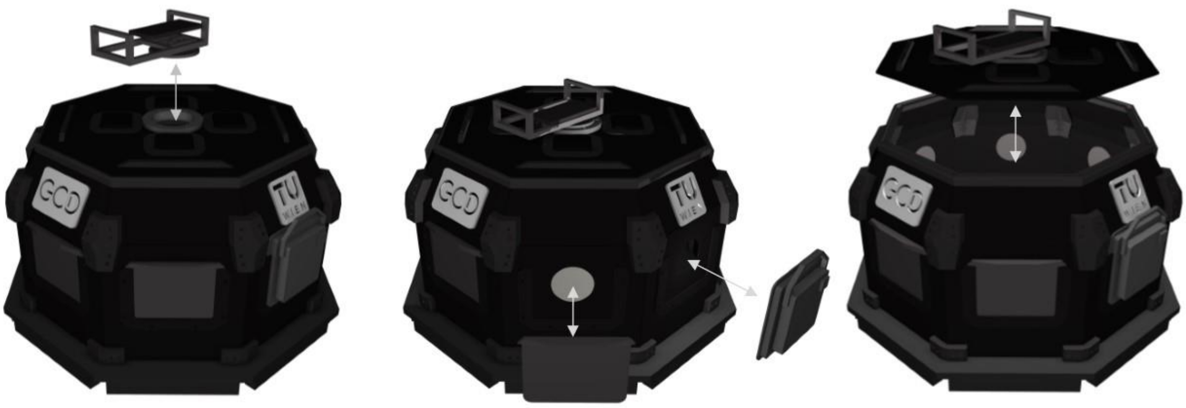


Figure 96. (a). smartphone attachment (b). changing position of directional light source (c). removable top cover with 4 diffused light sources

4.2.3.2 Workflow of the micro photogrammetry application

The remaining process is straight forward, the images (in total 9 images) gathered from desired materials (Fig.97) could be imported into Substance Designer as input nodes (Fig.98). After fewer adjustments, Substance Designer generates corresponding texture maps and publish the result as digital materials. These materials react correctly physically in digital render environments with different lighting conditions (Fig.99). This workflow allows architects to scan physical materials rapidly and process these into digital materials (Fig.100), which could also be used for digital architectural visualizations (Fig.101)

Figure 97. image gathering of flooring: 1. physical location 2. 8 multiangle images and one colour image without shadow, arrow symbolize the light direction

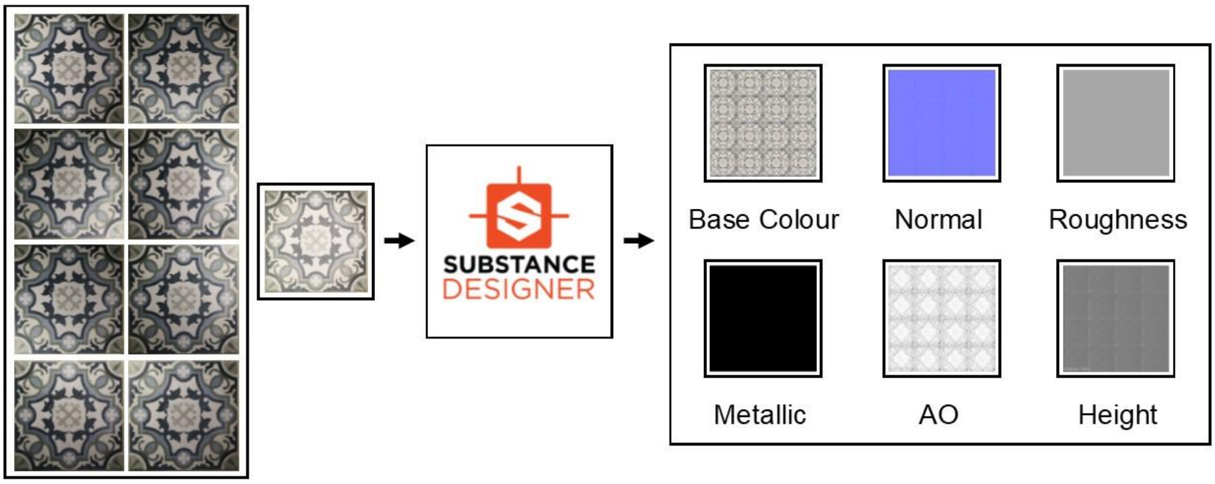


Figure 98. importing images into Substance Designer

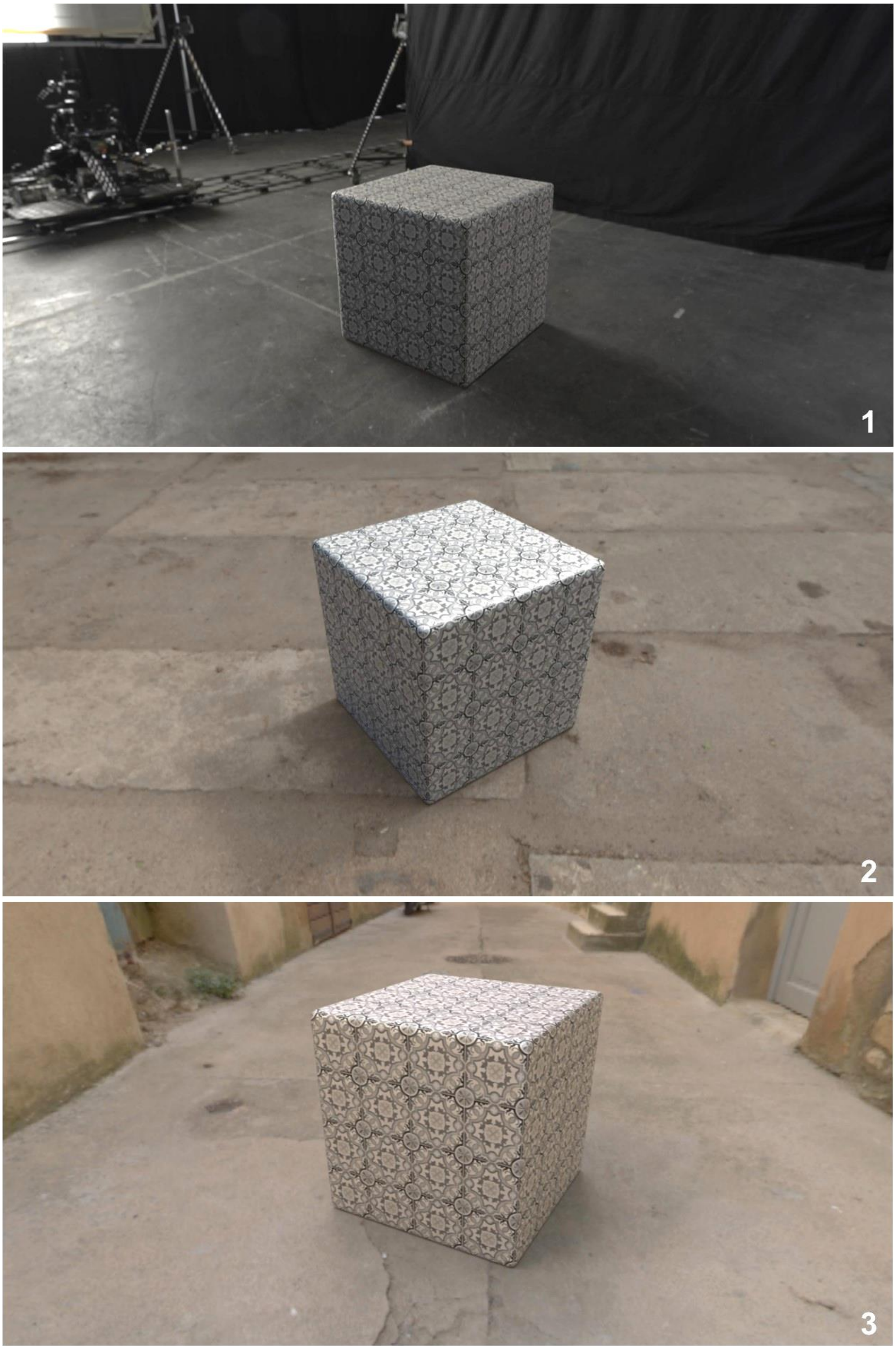


Figure 99. scanned tile flooring, the material acts correctly to corresponding lighting environments:1. cold light, studio 2. diffused light, cloudy day, outside 3. warm light, on street

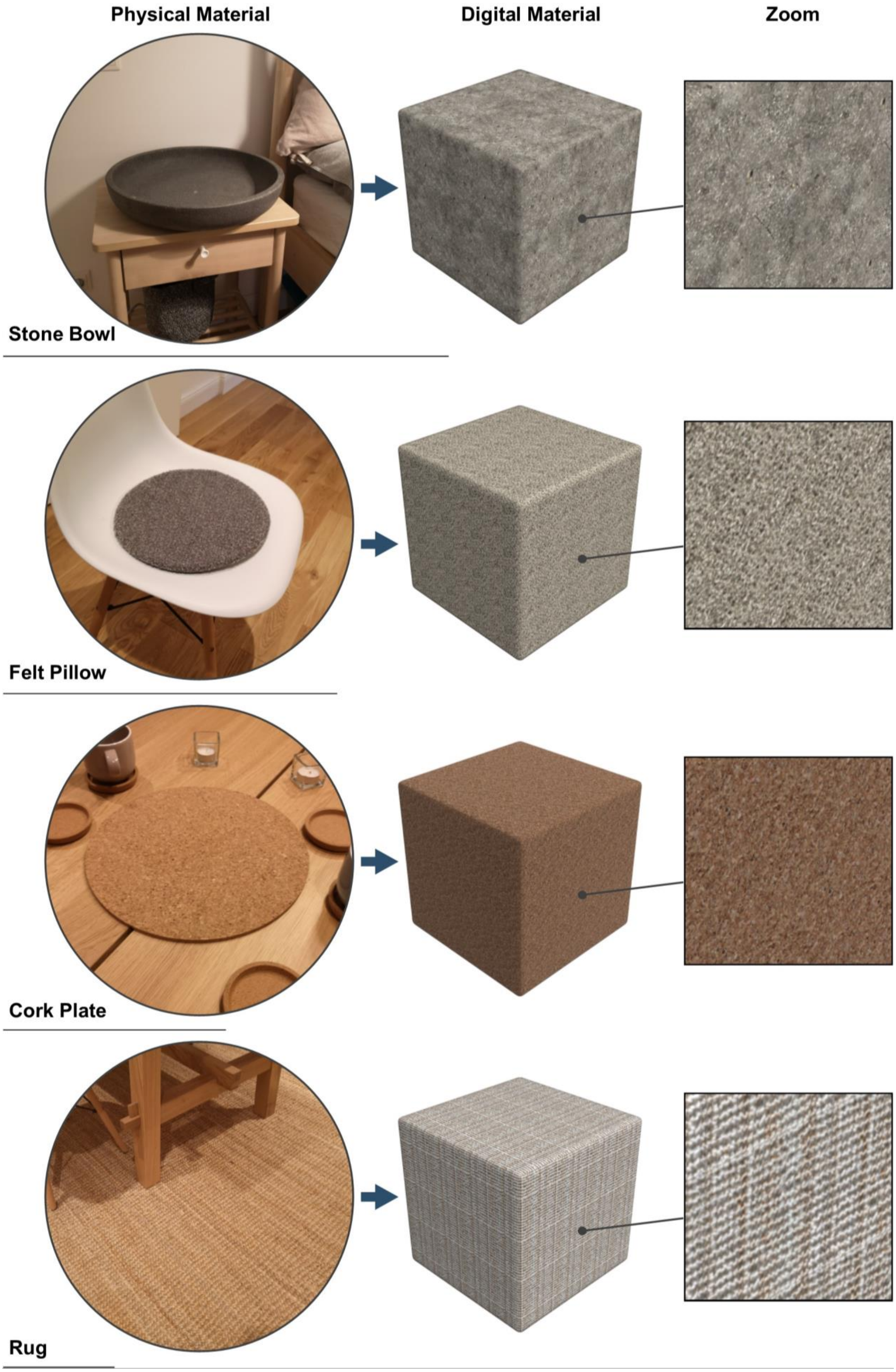


Figure 100. selection of digital material samples of scanned physical materials

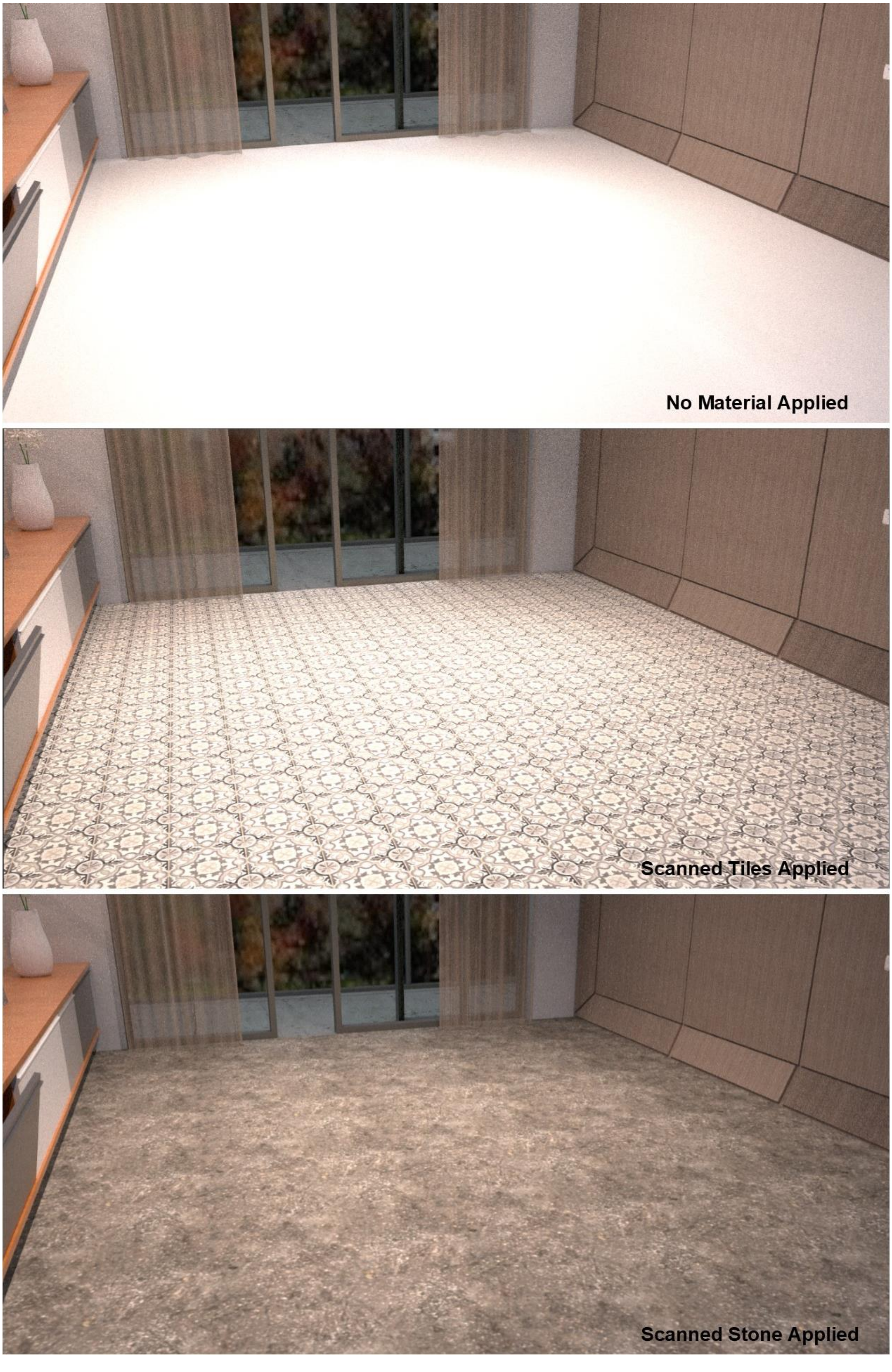


Figure 101. architectural rendering scene: scanned materials applied to V-Ray renderer for architectural visualization

4.3 Integration of the virtual reality workflow into the redevelopment process

The goal of this subchapter is to study the feasibility and usability of the virtual reality application for the redevelopment process. Specifically, photogrammetric results from the last chapter will be integrated into the Unity editor to create a virtual environment. By designing the VR scene and providing users with the possibility to navigate and interact with the environment, architects (and technical planners) could review the current condition, and preview the renovated condition and finished (furnished) condition of the existing contexts in a virtual environment during the preparation and planning phase, based on their own design. Moreover, the VR application could be used as a communication tool for customers, in which customers could also review the design and have the possibility to choose design elements according to their preferences (Fig.102). The first two topics of this subchapter are to introduce the practical implementation of the VR development from a hardware and software perspective. The final result will be demonstrated in the last topic of this subchapter (Fig.103).

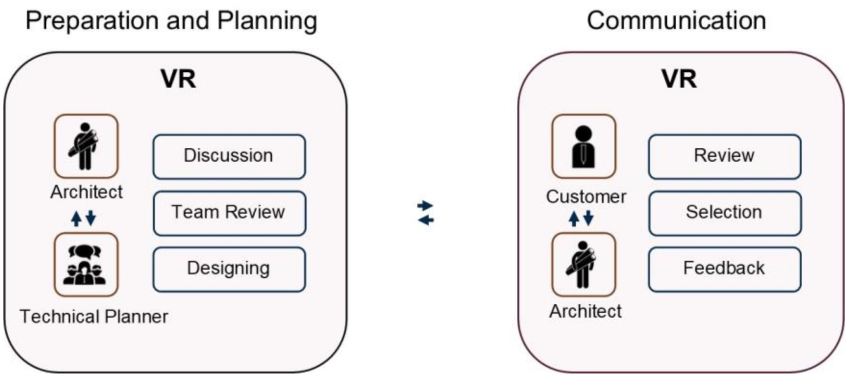


Figure 102. integration of the VR workflow into the redevelopment process

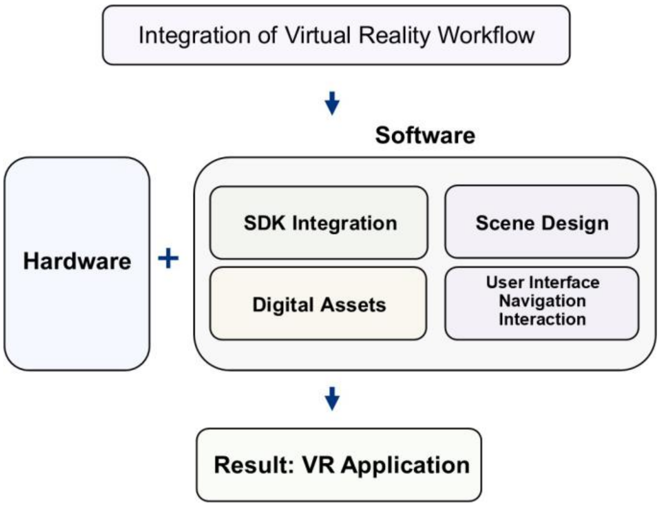


Figure 103. content structure of subchapter 4.2

4.3.1 Hardware

VR set

Oculus, as the first consumer VR HMD manufacturer, has not only one of the market-leading HMDs but also sophisticated integrated trackers and controllers such as the “Oculus Rift bundle” (Fig.104). The easy accessibility and stability of these hardware devices has made the Oculus Rift bundle one of most popular VR hardware choices. Therefore, the Oculus Rift bundle was chosen as the VR hardware for this thesis.

Figure 104. Oculus Rift bundle: HMD, controller and tracker

Computer

Additionally, a computer is also required for the development and the application of VR. Generally speaking, any computer could be used regardless of the manufacturer. However, to achieve the best immersive VR experience, the computer must have enough processing power to accomplish this task. In this thesis, a desktop computer from DELL will be used (Fig.105).

Figure 105. DELL XPS 8930. CPU: Intel i7 8700, GPU: GeForce GTX 1080

4.3.2 Software

4.3.2.1 SDK integration into Unity

Game Engine: Unity

Nowadays, there are several accessible commercial game engines which allow developers to create their own games. The most popular game engines are Unity3D (@Unity) and Unreal Engine (@EpicGames): Since Unity 3D and Unreal Engine both have free accessibility and numerous helpful plug-ins and online support, they are commonly used in the practices (Fig.106).

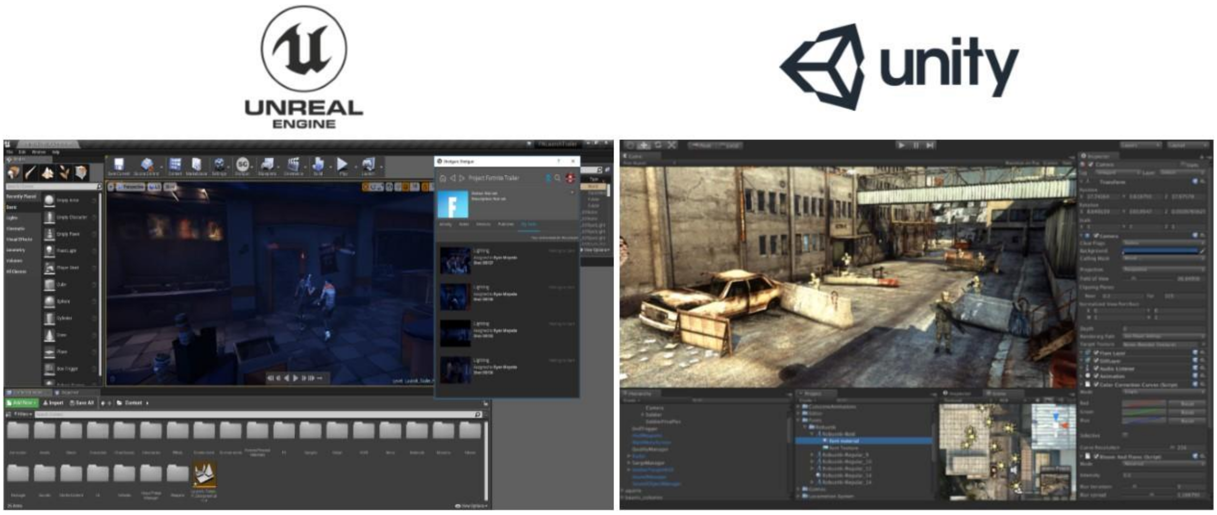


Figure 106. game engines: Unreal Engine and Unity 3D

Unity is beginner friendly and has the best accessibility, so it could be used as a professional or an amateur developer. The free version of Unity provides all the core components and functionalities to develop an application; with a clear user interface and software structure (Fig.107) and numerous offers of free third-party plugins and digital assets, Unity has made itself the best game engine for creatives. Therefore, Unity is chosen as the game engine for further development.

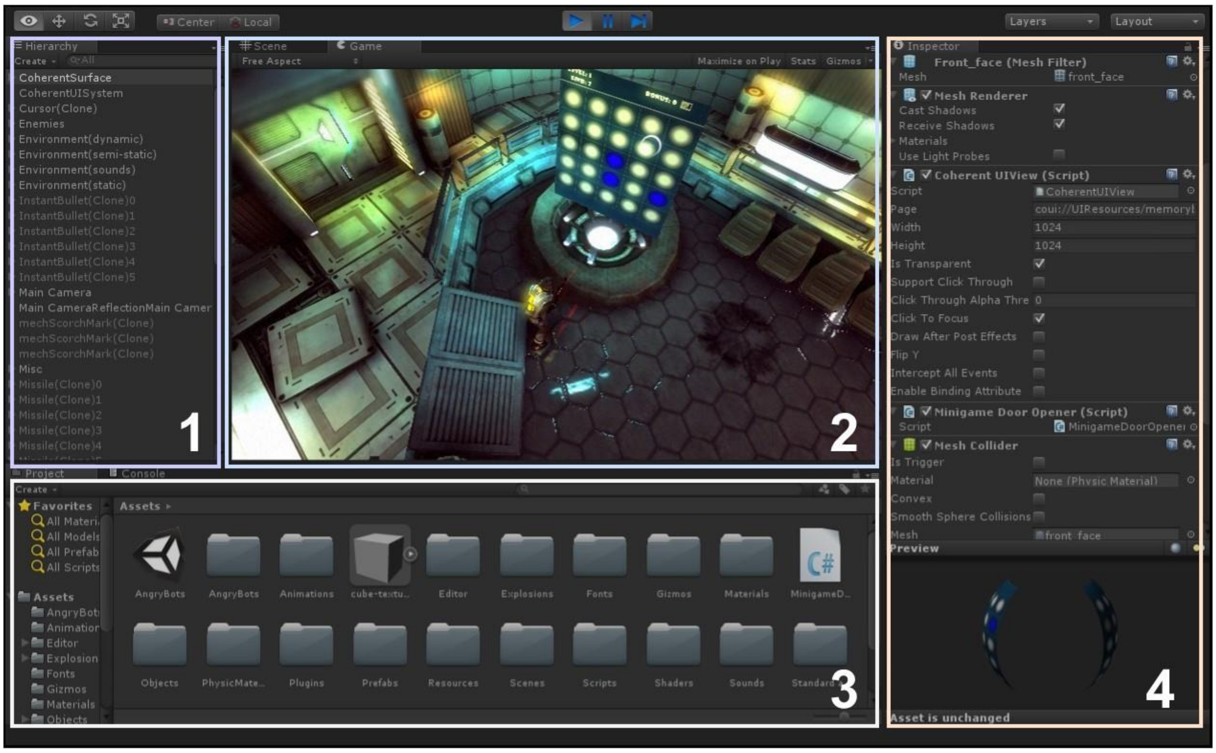


Figure 107. screenshot of Unity user interface: 1. hierarchy window 2. scene window 3. project window 4. inspector window

Oculus SDK

The integration of the Oculus SDK is straightforward since it could be downloaded online as a plug-in for the Unity engine. Besides numerous helpful components, the most essential components included inside the Oculus SDK bundle for development VR in Unity editor are (@Oculus):

- OVR Manager: The main interface between Unity and Oculus VR hardware.
- OVR Camera: The customized VR camera to replace the regular camera of the Unity editor. Instead of using Unity's monoscopic camera, this component is responsible for producing stereoscopic images based on the tracking system.
- OVR Avatar: This component could be placed into the scene inside Unity editor, representing the physical appearance of the user.
- OVR Player Controller: The script attached to the character in the Unity editor, this script is responsible for the navigating inside the virtual environment.

After the integration of the Oculus SDK, the modified version of the Unity editor has now all the necessary functions and capabilities to produces stereoscopic images, display a user's avatar (digital human representation), track the position of the user, and publish entire scenes as a VR application (Fig.108). Moreover, the modified Unity editor enables the communication between hardware devices during the whole development process.

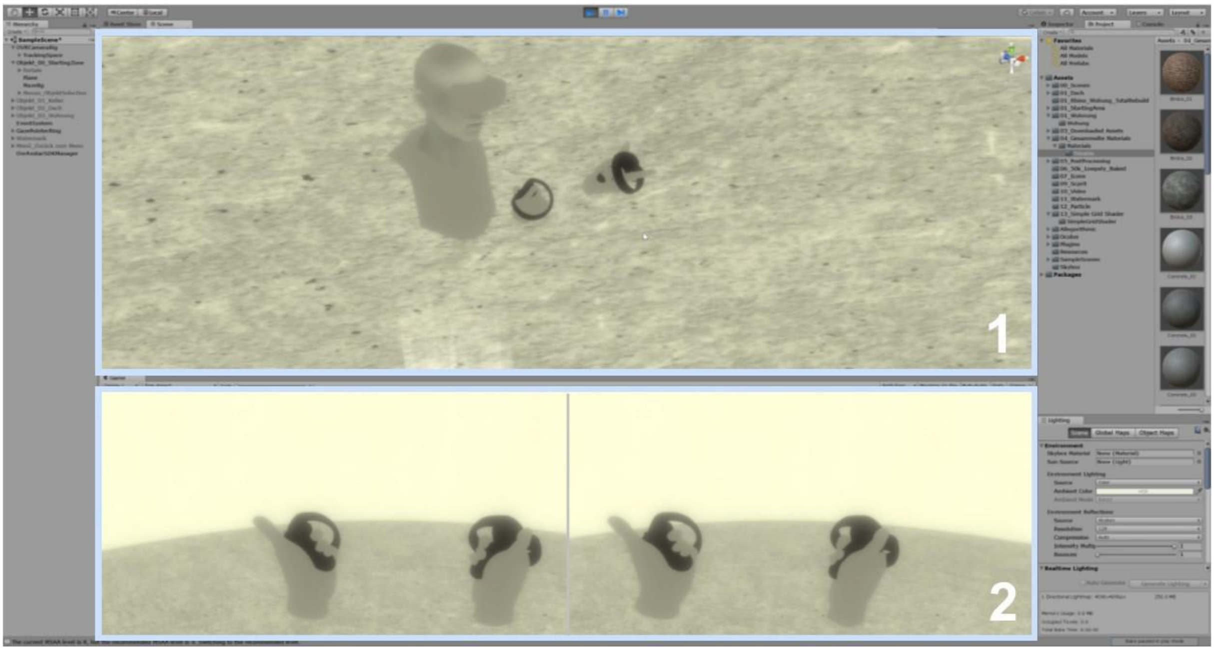


Figure 108. screenshot of modified Unity editor for VR development after the Oculus SDK integration:1. representation of VR user in scene window 2. modified stereoscopic camera preview instead of Unity's monoscopic camera

4.3.2.2 Digital assets

After loading various digital assets into Unity's project folder, all digital assets could be archived, sorted and from this point on used in the Unity editor (Fig.109). Cleaver placement and usage of these digital assets set up the scene and create a convincing digital environment.

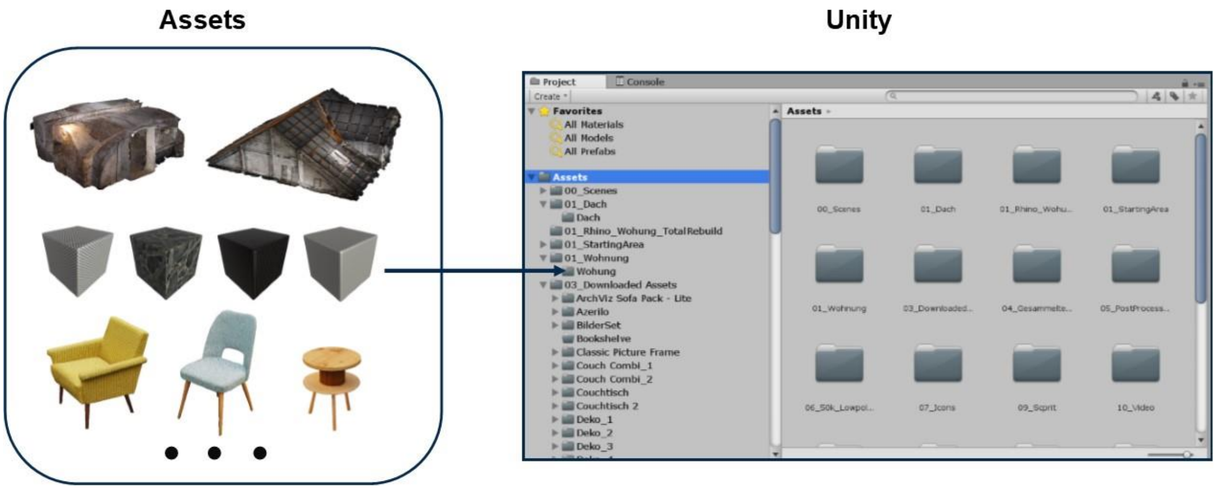


Figure 109. import of digital assets into the Unity project window

4.3.2.3 Scene design

Scene design could be compared with writing a script for a movie or a theatre play, it defines the scenario and events that the user observes and experiences inside the digital scene. To give the user best the story-telling experiences and possibility of making his own decisions, the scene will be constructed as described below (Fig.110):

- Starting area: neutral zone after the application starts, in this area, users have the possibility to familiarise themselves with the VR environment, navigation, and control. Furthermore, users have the possibility to select and enter into another environment.
- Photogrammetric results: the results of the photogrammetric scan could be entered and reviewed separately in the virtual environment. In this stage, architects or related experts have the possibility to re-engage into the site in the digital environment without extra cost and physical presence, which simplifies the design process.
- Presentation of the redevelopment process: in this environment, the result of the current situation, the renovated situation, and the completely furnished situation will be shown and will be created, that user can interact with. In the renovated environment, architects and other experts could experience the result of the redevelopment immediately and hold discussions and perform architectural changes to experience the different design varieties. In the last phase, the finished condition will be displayed, architects could “final-check” their design and it could be further used for the site owner or potential buyer as a communication tool, which could accelerate the purchase process by offering the “what you see is what you get” experiences.

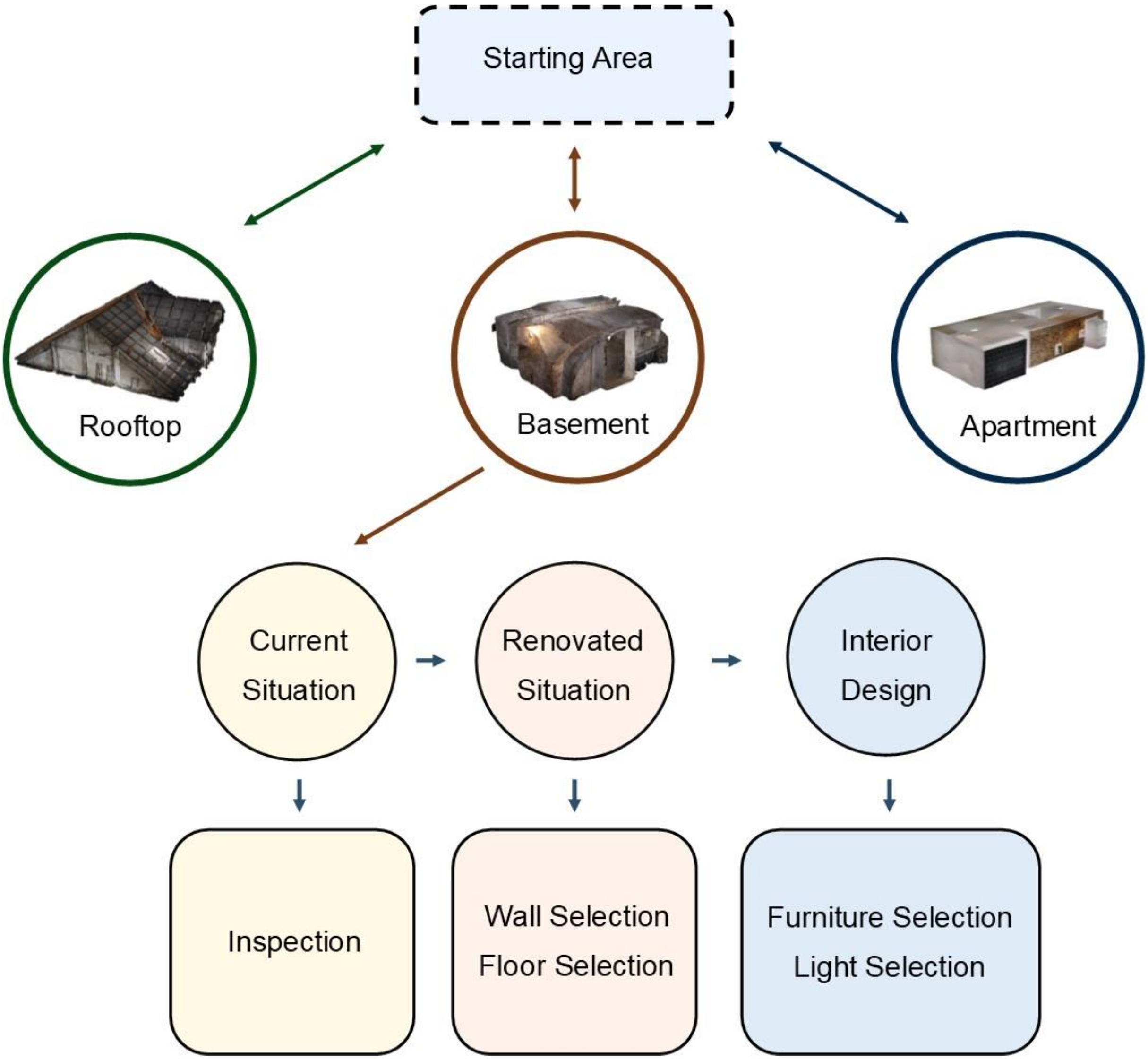


Figure 110. schematic structure of VR scene design

4.3.2.4 User interface, Navigation and Interaction

Having the possibility to navigate through different environments and interact with the environment in the scene is the most essential part of the VR application.
To achieve this, a user interface (UI) must be created to let the user select the options based on his own wishes. In the Unity editor, the integrated function “UI creation” allows developers to create “canvas-objects” such as buttons, text, images, and toggles without extra effort These premade base elements could be placed into the scene. And by defining “which event should happen after which element is triggered”, a functioning menu system could be created (Seifert 2015). The menu system could be placed directly on the screen (2D) or into the digital world (3D); since VR is a world space-based environment, a world space-based menu is preferably used in VR.
Therefore, a world space-based menu is created and placed into the scene, it allows the user to select and navigate through different virtual environments and gives the user the possibility to modify specific objects inside virtual environments (Fig.111).

Figure 111.world space-based menu to select furniture element in the VR application

With the integration of the Oculus SDK, Unity recognizes required VR hardware to build an interactive system based on these devices. Specifically, the HMD, controller and tracking system could be modified in the Unity editor: by assigning them specific tasks and functions, these devices allow the user to interact with the environment by selecting specific elements from the menu. This is achieved primarily though collaboration between the HMD and the controller (Fig.112):

- Selection: the simplest way to select elements or any objects in VR by looking towards to it for a defined period of time. With a ray-cast script attached to the camera, the direction of sight from the user (ray of sight) will be simulated, as soon as this invisible ray collides with another object in VR, the collision will be registered and a gaze ring will appear on top of the object, which means this specific object is selected and the user could take further decisions.
- Control: two controllers (Oculus Touch) are the devices which will be hold in hands of the user and these function as the primary input device. While the joystick on the left controller controls the movement inside the virtual environment, the button on the right controller acts as the key to confirm the selection. It is worth mentioning, that movement inside the virtual environment could cause so-called “motion sickness” (Jerald 2016), which could cause dizziness for the user -in other words, the movement control inside VR should not be performed rapidly.

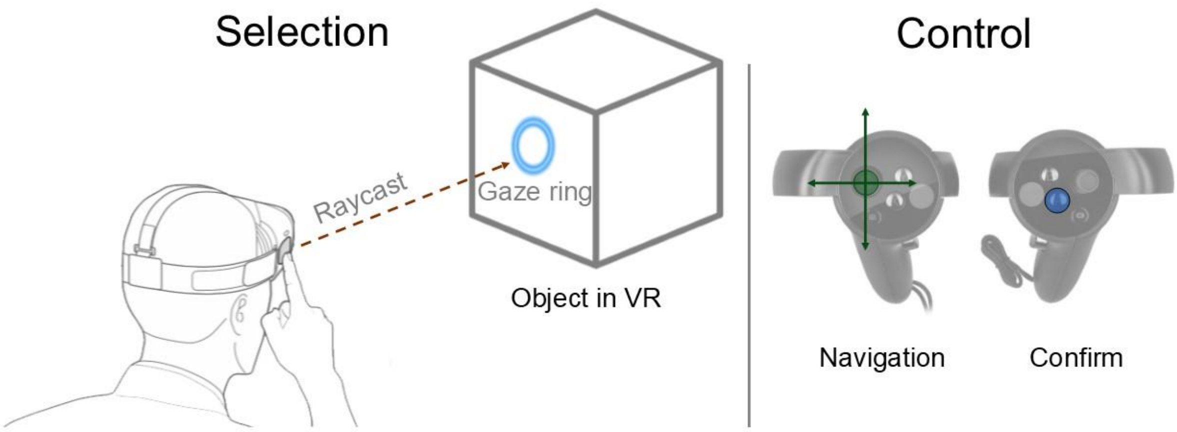


Figure 112. method of selection and control inside virtual environment

4.3.3 The VR Application

The technical implementation of the VR application in the Unity editor is a straightforward process. After implementing various additional digital assets, menus and navigation control possibilities, the development of the VR application in Unity is accomplished. The final step in the VR workflow is to publish the application as an executable file format on the PC system (e.g. as .exe). The result is a structured order of files with one executable file in it. This executable file could be launched on any pre-defined PC system, on the condition that the PC system has enough processing power and is also connected with the necessary VR hardware.

The finished application allows users to navigate through different environments in the starting area (Fig.113), review the photogrammetric scan of the existing contexts (Fig.114) and preview the different stages of the redevelopment process (Fig.115), moreover having the possibility to modify the objects inside them (Fig.116). Lastly, scanned furniture and materials could also be implemented within the virtual environment to enhance the capability of the VR application (Fig.117).

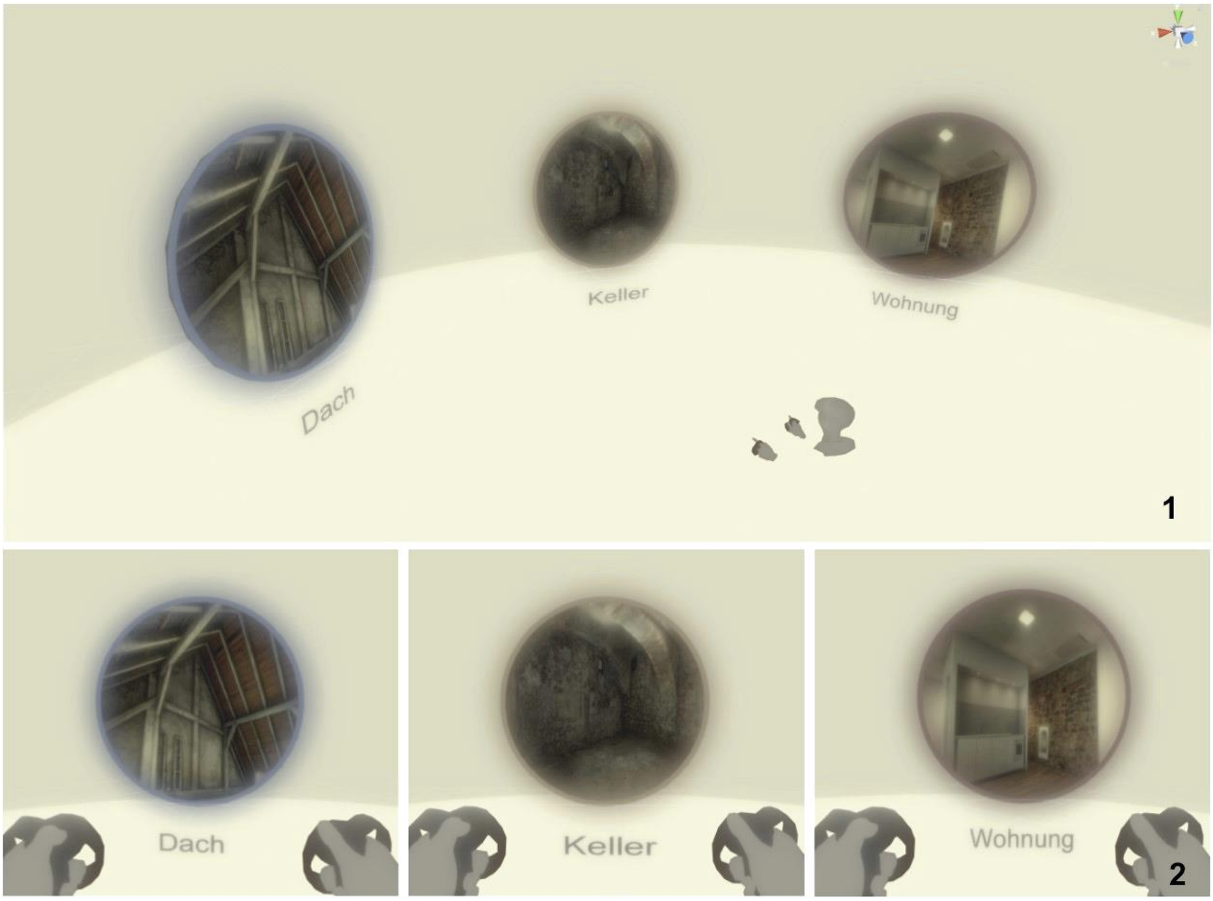


Figure 113. the starting area of VR application: 1. top down overview 2. selection of the environments

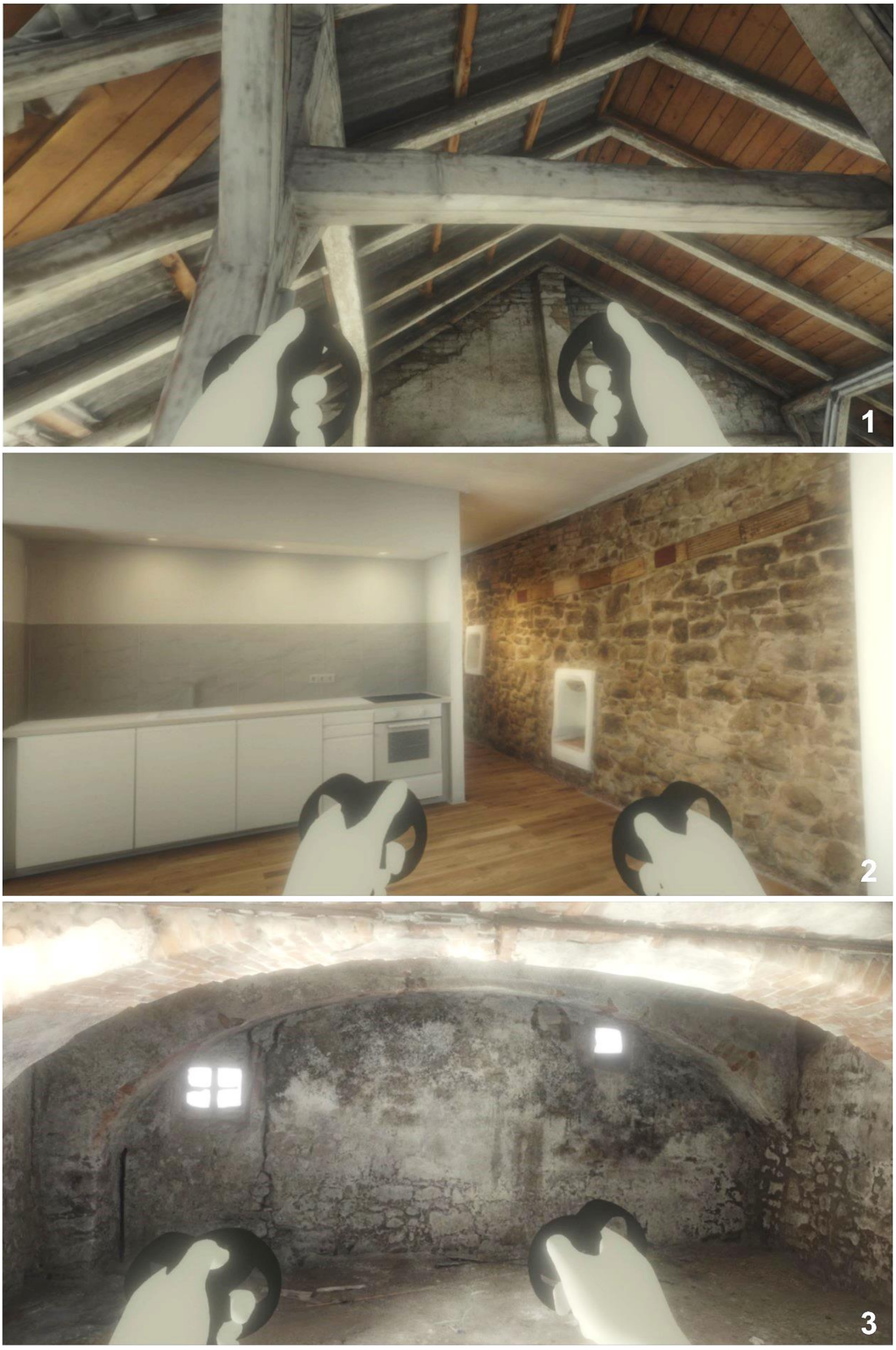


Figure 114. screenshots of three different environments in VR application: 1. rooftop 2. apartment 3. basement

Figure 115. showing stages of the redevelopment process of basement in VR application: 1. undeveloped condition 2. renovated condition 3. finished condition of the basement

Figure 116. interacting with objects: 1. selecting flooring 2. selecting wall color 3. selecting lighting 4. selecting furniture

Figure 117. scanned digital assets applied in the VR application. 1. tile flooring 2. stone table 3. rug and yellow armchair

After setting up the VR system, the real-world usage of the VR application is uncomplicated. However, since users are visually isolated from the physical world, to prevent any possible physical accident during VR usage, at least 2x2 m space without any obstacles should be assured for users' safety (Fig.118).

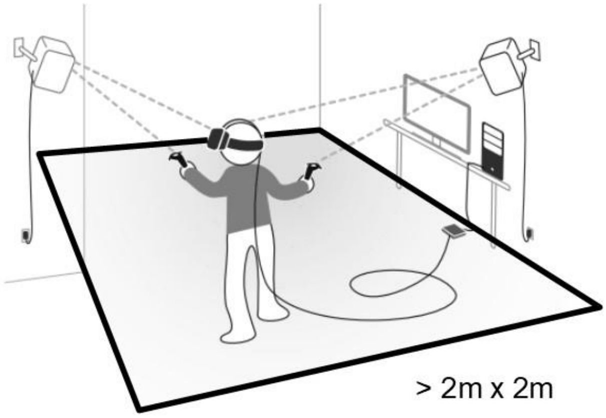


Figure 118. safety measure while using VR application

After a short introduction to the hardware and control system in the VR application, users can explore the digital environments independently. Since VR simulates the humans' natural perception, no overcomplicated introductions are necessary during usage, as users familiarize themselves with the VR hardware and application in a short period of time (Fig.119). This means the use of VR systems and the application is not only for experts, but is also suitable for widely different types of users.

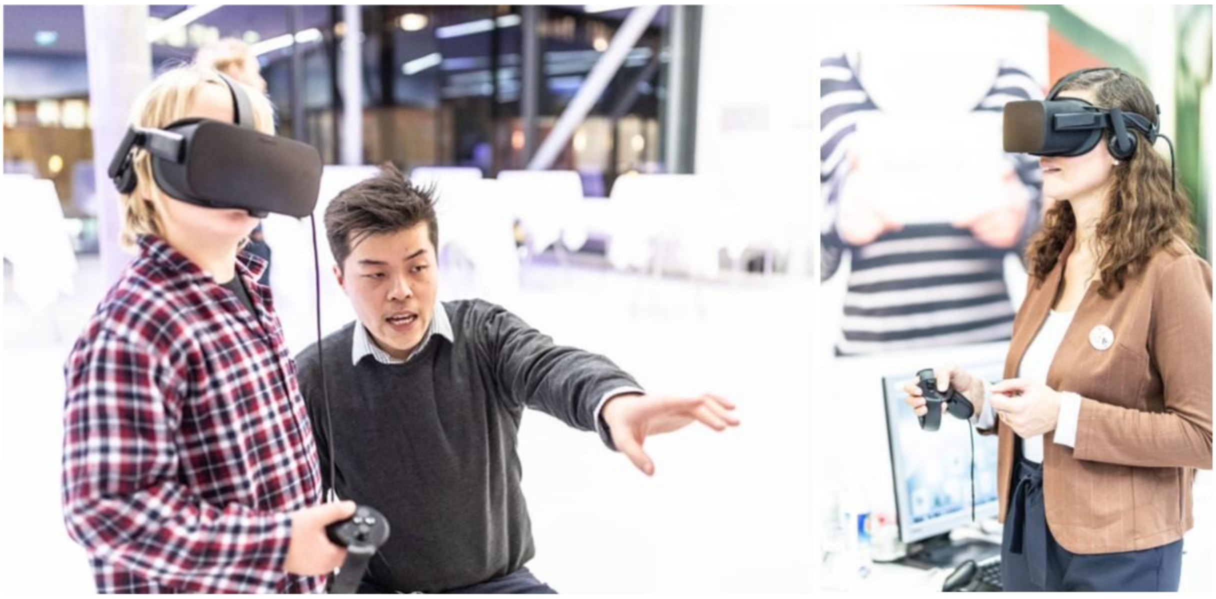


Figure 119. live demonstration of the application at innovations contest award ceremony of Burgenland 2018

CHAPTER 5

Conclusion and Outlook

Current challenges during the redevelopment process in existing contexts are the dependence on laser measurement or manual measurement: while laser measurement is cost intensive, the manual measurement method is often inaccurate. The second current challenge is the upcoming 2D-based documentations obtained from these traditional measurement methods, these extensive and overcomplicated 2D documentations could cause misunderstanding between architects and technical planners during the redevelopment process. Additionally, communication with customers based on 2D documentation is tedious.

With the photogrammetry application examples and VR implementation shown in this thesis, the current digital workflow of architectural redevelopment in existing contexts process could be adapted with a reasonable effort. The new adapted version of the workflow offers architects new possibilities and capabilities to accomplish building redevelopment tasks. With the applications demonstrated in the practical work of this thesis, it is possible for architects to perform photogrammetric surveys to obtain reliable 3D textured models of existing contexts. Therefore, manual measurement or hiring professional survey firms are not necessary in some situations (exception: the gallery, or similar situations). By combining object scan and material scan techniques, architects could also rapidly produce their own digital assets to study the design or fulfill specific wishes of their customers. Moreover, with integration into virtual reality, depending on the design and intention of the scene, it could be used as a 3D-based visual presentation tool, in which overcomplicated 2D documentation is no longer needed. Considering all these aspects, the adapted workflow with photogrammetry and virtual reality could help building redevelopment in existing contexts become a more efficient process by saving time and simplifying communication during the multi-disciplinary planning process. Moreover, the adapted workflow could also improve the communication between architects and decision-makers (financial, political and commercial) to accelerate the decision-making process.

Even though the photogrammetric and virtual reality workflow enhances the design process in many ways, the adaptation and integration of photogrammetry and VR workflow could require significant effort in the beginning, which could take days of work to accomplish. However, with real-world practices and experiences, the integration could be achieved much faster. It is still hard to tell how much effort the integration will require due to the numerous variable and uncertain circumstances (e.g. scale of project), nevertheless, architects could estimate efforts based on their experience. Moreover, it is advisable to have one specialized personal in the team for this task, or outsource the task (e.g. to specialized rendering offices).

Moreover, there are still some issues involving photogrammetry and VR workflows which could be improved.

Although a photogrammetric survey is indeed uncomplicated to perform, if a room consists mostly of featureless surfaces (walls, floor without texture), evaluation of these images is difficult, the result may not be able to be reconstructed. As the gallery in Eisenstadt was recorded, it only consists of large windows and white painted wall surfaces with glossy white furniture inside it, and as a result, the photogrammetric reconstruction software could not extract enough features to recreate the site. This problem could hopefully be solved by projecting irregular patterns onto the featureless surfaces to increase the surface-texture complexity.

Moreover, the most demanding part of photogrammetric workflow is to revise the digital photogrammetric 3D model during post processing; the photogrammetric reconstruction software is fast and precise, however, none of its algorithms can distinguish or define the scanned objects based on their material or utilization: Where humans can easily distinguish between door/windows/wall and categorize these objects, unfortunately, none of the algorithms today are compatible with doing so. This work still relies on humans selecting and separating each component manually. In other words, scanning to BIM is still an open problem in the architectural domain, and photogrammetry is no exception.

Additionally, the integration of results into a game engine (Unity) for VR application development is straightforward, however, the production or enactment of the scene is strongly computer-graphical and computer programming-related. In other words, architects without fundamental knowledge of programming or computer graphics could not master the workflow quickly. To compensate for this, another third-party plugin for the game engine (or stand-alone software) should be created specifically for architects to navigate and setup VR in a simplified way, and also provide users with the possibility of choosing certain design variations.

Nonetheless, this adapted workflow could be so efficient and practical in the future that photogrammetry survey and design in VR even become the standard architectural workflow. With better hardware manufacture and increasing computing capability, photogrammetric surveys and VR could become even more proficient and convenient. This is especially true with the development of multiple lens smartphones, which are fundamentally better than single lens cameras, since they can record stereoscopic pictures from a single camera position. Moreover, light field cameras could also be advantageous since the camera sensor can save the information about the direction of light, which traditional cameras are not capable of doing.
Moreover, combined usage of AR (e.g. Microsoft HoloLens2) with photogrammetry and VR could further enhance the workflow. With the possible integration into building information modeling systems, this workflow or modified version of it could be the state-of-the-art method for architects or any design discipline to break through the 2D-based design boundary.

The possibility and opportunity of this workflow is promising, and with further hardware and software development and improvement, it might represent the new chapter of the digital era in architectural work.

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List of Figures

Abbreviations

AR	augmented reality
BOOM	binocular omni orientation monitor
BIM	building information modeling
CPU	central processing unit
CAD	computer aided drawing
DSLR	digital-single-lens reflex
FPS	frames per second
GPU	graphics process unit
HMD	head mounted display
UI	user interface
RAM	random-access memory
SDK	software development kit
VR	virtual reality