A FRAMEWORK FOR REALISTIC VIRTUAL REPRESENTATION FOR IMMERSIVE TRAINING ENVIRONMENTS.

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ABSTRACT: *As mixed-reality (XR) technology becomes more available, virtually simulated training scenarios have shown great potential in enhancing training effectiveness. Realistic virtual representation plays a crucial role in creating immersive experiences that closely mimic real-world scenarios. With reference to previous methodological developments in the creation of information-rich digital reconstructions, this paper proposes a framework encompassing key components of the 3D scanning pipeline. While 3D scanning techniques have advanced significantly, several challenges persist in the field. These challenges include data acquisition, noise reduction, mesh and texture optimisation, and separation of components for independent interaction. These complexities necessitate the search for an optimised framework that addresses these challenges and provides practical solutions for creating realistic virtual representations in immersive training environments. The following exploration acknowledges and addresses challenges presented by the photogrammetry and laser-scanning pipeline, seeking to prepare scanned assets for real-time virtual simulation in a games-engine. This methodology employs both a camera and handheld laser-scanner for accurate data acquisition. Reality Capture is used to combine the geometric data and surface detail of the equipment. To clean the scanned asset, Blender is used for mesh retopology and reprojection of scanned textures, and attention given to correct lighting details and normal mapping, thus preparing the equipment to be interacted with by Virtual Reality (VR) users within Unreal Engine. By combining these elements, the proposed framework enables realistic representation of industrial equipment for the creation of training scenarios that closely resemble real-world contexts.*

KEYWORDS: *Digital twin; 3D reconstruction; Virtual reality; Laser scanning; Photogrammetry; Training simulation; Unreal Engine.*

1. INTRODUCTION

In recent years, the increased availability of mixed-reality (XR) technology has spurred the exploration of virtual reality training environments, which showcase their immense potential in enhancing training effectiveness across various domains(Abulrub et al., 2011). By reducing expenditure associated with travel and physical resources, safety training that has been delivered via virtual methods is predominantly more cost-effective than non-virtual alternatives, without sacrificing training effectiveness (Adami et al., 2021) (Stefan et al., 2023).

Virtual Reality (VR) can present us with realistic replications of real-world situations with a high degree of accuracy, and immersive virtualised training scenarios can significantly improve participant engagement when compared to equivalent training using conventional methods (Sacks et al., 2013). Trainees presented with a virtual environment can engage with high-risk scenarios without actual danger. The elimination of risk fosters confidence and risk-free experimentation, which has a significant positive impact upon post-training technical proficiency (White & Jung, 2022). Regarding the attitude of trainees towards professional learning content, Loosemore and Malouf (Loosemore & Malouf, 2019) suggest that there is “a need to adapt safety training to create more emotional connection” between the trainees and their learning within the construction industry, and that “New technologies such as virtual reality may be useful this context since through [life-like] immersion in the work environment and simulation of workplace accidents, they are able to create a stronger emotional connection with the subject matter.” This suggestion is supported by Newton, Wang and Lowe (Newton et al., 2015) who find that “incongruously, results indicate that user’s reporting their experience of virtual reality score that experience higher in presence terms than users experiencing the physical world,” indicating that virtual experiences may be more emotionally engaging and more impactful for trainees than real-world experiences alone. This calls us to re-examine our approach to training and education as we begin to see XR technology as an effective tool to enable trainees to connect theoretical knowledge and practical application.

The standard of these simulations is influenced by the quality of virtual representation. High-fidelity 3D illusions bridge the gap between physical and digital environments and enhance the task-oriented performance of the

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trainees (Slater, 2009) and so highly-realistic virtual assets may improve the effectiveness of the virtual experience.

1.1 3D Scanning Methodologies

To elevate the authenticity and realism of virtual training, exploring 3D scanning methodologies (such as photogrammetry and laser scanning) present exciting possibilities as potential solutions for highly realistic representation within VR scenarios. By employing advanced 3D scanning technologies, we can capture with accuracy the dimensions and intricate surface details of real-world equipment and environments. After sufficient data has been captured with scanning hardware, the data will be manipulated through a pipeline of various specialized 3D modelling software to create a mesh that may be rendered by a games engine.

There are practical challenges associated with the application of 3D scanning techniques which must be addressed, such as site-access for data acquisition, followed by noise reduction and asset optimization. To conduct the training, the user will be expected to manipulate the asset, or parts of the asset, using virtual reality hardware. Therefore, not just aesthetic accuracies, but realistic interaction and functionality will also be essential. Equipment which has independently moving components will have to be separated into dynamic and static bodies to facilitate independent movement and interaction within the virtual environment.

1.2 Goals of this Article

Our effort to establish a framework that adheres to industry best practices has been in collaboration with The Faraday Centre, recognised for their expertise in electrical engineering training. Ordinarily, The Faraday Centre delivers training using out-of-service switchgear that has been refurbished or donated to the Centre, so that trainees can receive hands-on practical training with switchgear up to 33kV. A significant challenge presented by electrical engineering equipment is that there are high costs associated with the newer, higher-voltage switchgear, thus making their acquisition impractical. A virtual training environment (VTE) offers a cost-effective alternative to simulate operation of this high voltage equipment for training purposes. Our data-driven approach hopes to ensure that the virtual representations closely mirror their physical counterparts.

Therefore, we believe that establishing a framework encourages the integration of virtual technologies for industrial training scenarios. Our objective is to provide insights into the scanning methodologies, challenges faced, and available solutions in capturing the details of real-world environments, equipment, or other assets. To achieve this, this paper will review the current technology and methodologies used to emulate real-world equipment and their processes within a virtual context. Drawing inspiration from methodologies employed in data-driven digital twinning pipelines (Pan et al., 2022), both photogrammetry and laser-scanning applications are integrated within this framework and their compatibility with the development of contemporary professional training for high-risk environments is discussed. The framework proposed is capable of systematically addressing each obstacle, thereby ensuring a seamless transition from physical equipment to the creation of highly realistic virtual training environments.

This paper is organized as follows: **section 2** will look review production pipelines, methods and motives for the creation of such data-driven virtual assets. **Section 3** presents an overview of the technology required to scan a 3D object and recreate it as 3D virtual asset. **Section 4** will report the framework we have developed as a solution to the challenges presented when developing realistic VR-ready assets from high-voltage switchgear scan-data.

2. METHODS FOR REALISTIC VIRTUAL REPRESENTATION

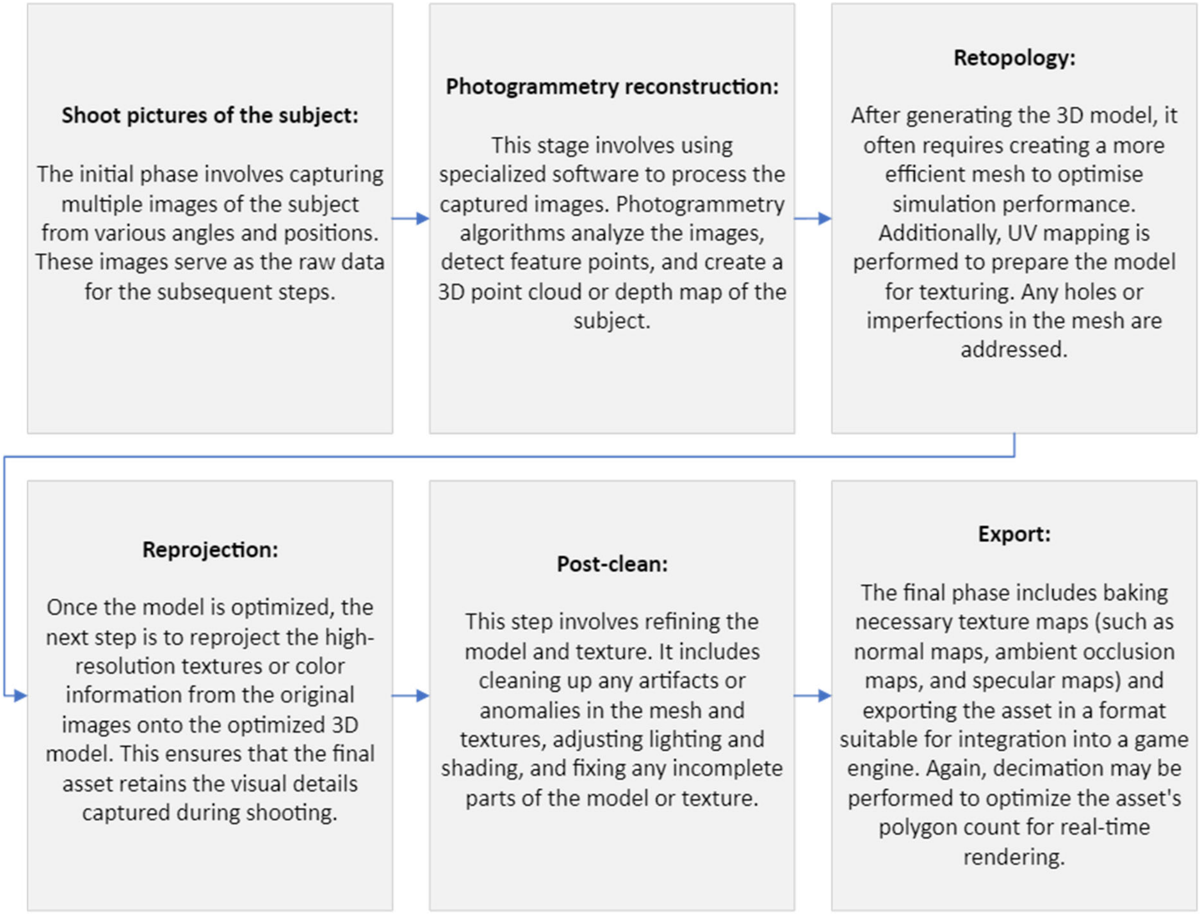
Virtual representation encompasses the creation of digital reconstructions of real-world subjects, including those with glossy surfaces like switchgear equipment. Specular (mirror-like) reflections can challenge 3D data capture methods like laser scanning and photogrammetry, reducing the usefulness of output models (Frost et al., 2023), therefore we will review approaches designed to address issues associated with capturing accurate data.

Another challenge involves minimizing the computational power required for rendering our results in a real-time application. Two viewpoints (one for each eye) must be rendered, making VR susceptible to difficulties with framerate, which will be affected negatively by superfluous model complexity. Therefore, our review will be extended to provide an overview of various methods to clean and simplify our results.

2.1 Photogrammetry

Photogrammetry is a 3D surveying and modelling method which has the major advantage of being low-cost, portable, flexible and is capable of delivering highly detailed reconstructions. Three-dimensional information about objects or environments is obtained by analyzing a dataset of two-dimensional photographs.

Photogrammetry relies on the identification of feature points on or within the object being scanned. Areas of the subject with aspects like colour variation, surface imperfections, or details such as dust and grime must be adequately captured to be reconstructed. Significant overlap across multiple images in the dataset is crucial to ensure an ample supply of contrasting, unique points. Observed similarities across images is used to reinforce the confidence of the photogrammetry software in determining the 3D positions of each point. Available photogrammetry software options are discussed in Section 3.



Shoot pictures of the subject:

The initial phase involves capturing multiple images of the subject from various angles and positions. These images serve as the raw data for the subsequent steps.

Photogrammetry reconstruction:

This stage involves using specialized software to process the captured images. Photogrammetry algorithms analyze the images, detect feature points, and create a 3D point cloud or depth map of the subject.

Retopology:

After generating the 3D model, it often requires creating a more efficient mesh to optimise simulation performance. Additionally, UV mapping is performed to prepare the model for texturing. Any holes or imperfections in the mesh are addressed.

Reprojection:

Once the model is optimized, the next step is to reproject the high-resolution textures or color information from the original images onto the optimized 3D model. This ensures that the final asset retains the visual details captured during shooting.

Post-clean:

This step involves refining the model and texture. It includes cleaning up any artifacts or anomalies in the mesh and textures, adjusting lighting and shading, and fixing any incomplete parts of the model or texture.

Export:

The final phase includes baking necessary texture maps (such as normal maps, ambient occlusion maps, and specular maps) and exporting the asset in a format suitable for integration into a game engine. Again, decimation may be performed to optimize the asset's polygon count for real-time rendering.

Fig. 1: A Photogrammetry process diagram showing an overview of the various stages from data capturing to a simulation-ready asset

The accuracy of camera alignment and the quality of the created asset is determined by consistency across the data obtained from the input images. In cases where the object's surface lacks distinctive features, challenges arise in achieving accurate surface reconstruction. According to Schiach, the objects best suited for automated image-based 3D reconstruction methods feature amorphous geometries, structured surfaces, numerous edges, and exhibit inhomogeneous colouring. Objects that yield poor or no results typically have monochrome, translucent, reflective, or self-resembling surfaces (Schaich & Fritsch, 2013). Dark materials, insufficient lighting, and changes in lighting can all have detrimental effects on the image quality and may prevent the photograph from registering as correctly aligned. Methods we may employ to optimise the conditions in which we capture data include strategic distribution of light sources to eliminate shadows, applying a coat of spray to make the surface more responsive to scanning, cross polarisation techniques, or by using some combination of these methods (Noya et al., 2015; Porter et al., 2016).

2.1.1 Capture methods

To capture a static object, the photographer moves around the subject, taking multiple pictures from various viewing angles. Collecting every angle may be made difficult if the object is quite large and/or positioned inconveniently for photo-scanning purposes, meaning a complete scan may be impossible without repositioning the object. For the feature detection algorithms to run correctly, the features of the input images must remain consistent. Therefore, if we wish to reposition the object, we must take the additional step of separating desirable features of our subject from undesirable inconsistencies from background visual information. Typically, this involves manually applying masks to each input image, a potentially time-consuming process (Farella et al., 2022), even with expediating background removal features like semantic segregation (Chen et al., 2017; Kang & An, 2021; Ronneberger et al., 2015).

Alternatively, a camera configuration with strategic lighting can be set up to automate the masking process. Background interference may be avoided by ensuring the scanned object is well-lit against a dark, featureless background. This allows for the target to be rotated and repositioned in front of a camera which may remain fixed, providing sufficient captured data from various viewing angles, without the feature detection algorithms being disrupted by undesirable information. The effect of this method may be improved by strengthening the lighting of the foreground to heighten the contrast between the foreground and background. This lighting can be provided in different ways, the object may be homogenously lit with LEDs from various angles, or a piece of equipment such as a ring light may be employed; both may sufficiently eliminate shadows.

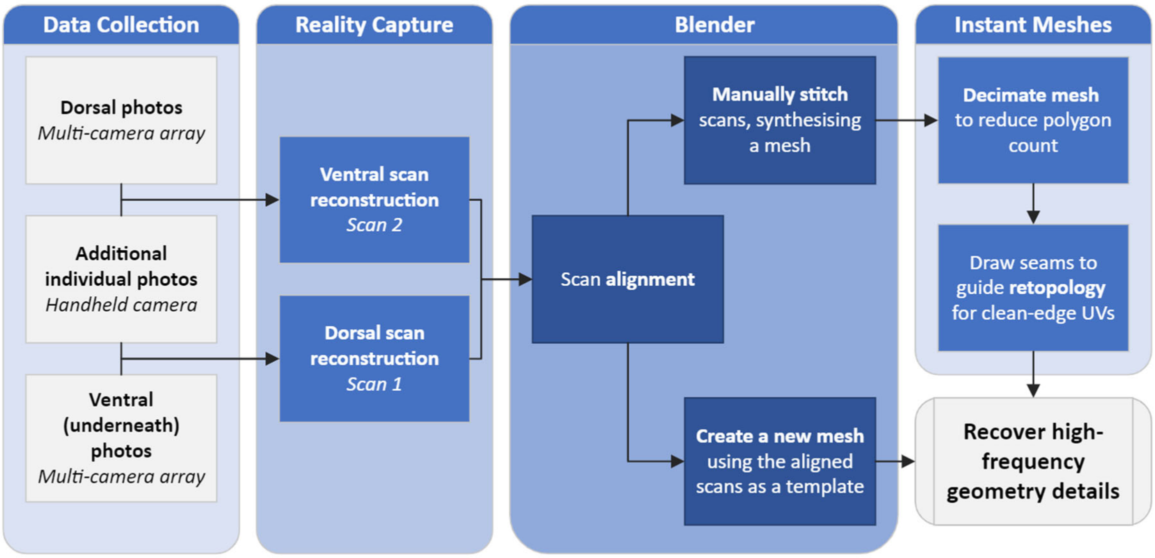
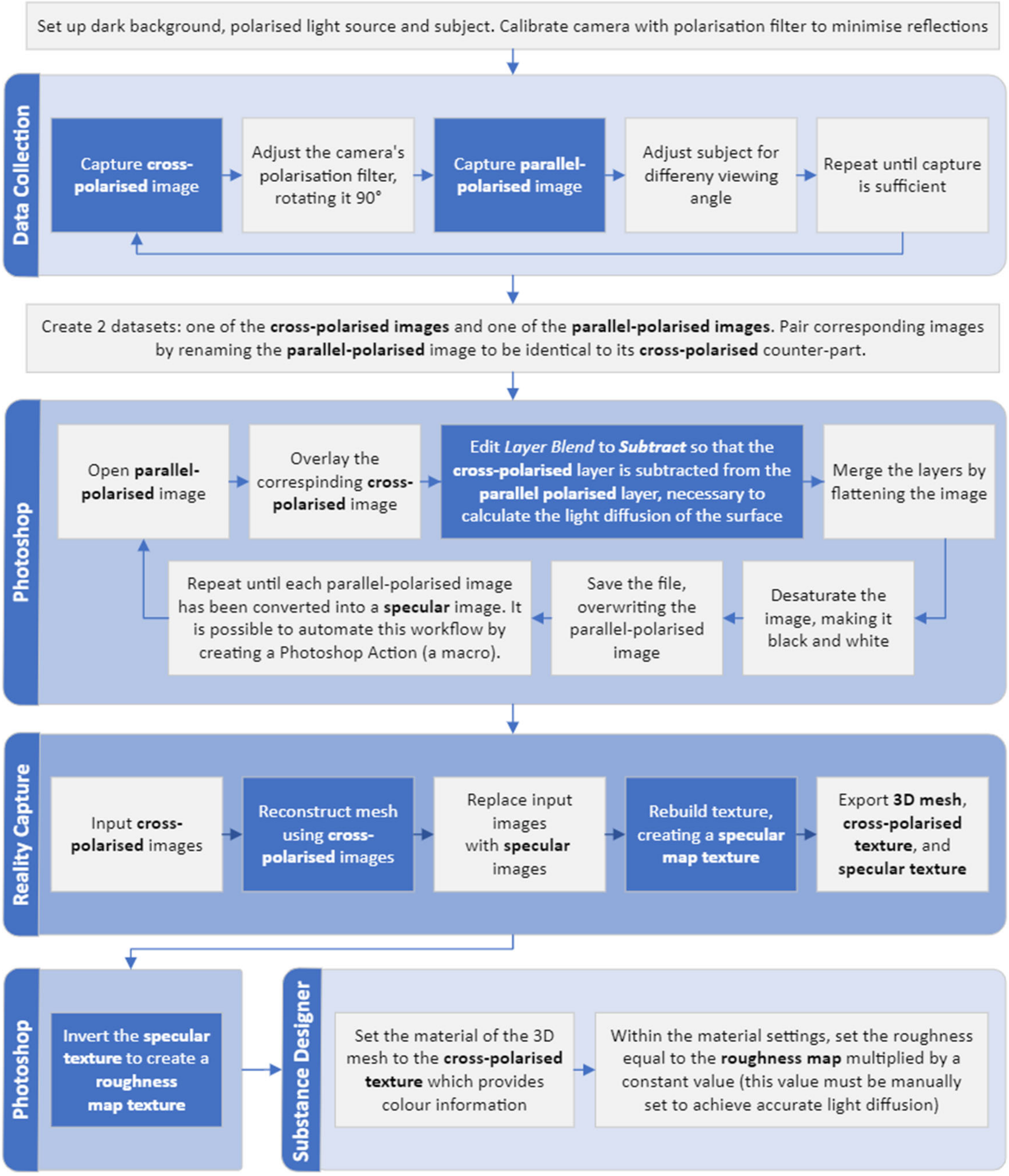


Fig 2: A flowchart describing the process used to create a clean asset from a photogrammetry reconstruction using a multi-camera array to capture a turtle (Bot et al., 2019). The software used is included. Recovering high-frequencies geometry details will be expounded upon in Section 2.3.

To capture dynamic objects, a single camera is unsuitable as it presents a high risk of capturing inconsistent data due to movement of the subject. Therefore, a multicamera array is used, which typically consists of 4 to 30 cameras on tripods or metal rods, with all of them pointing towards a central area. This “rig” of specially calibrated lights and cameras permits efficient and simultaneous data capture from various angles to ensure consistency across source images. An alternative method is the use of synchronized video with a common motion (e.g., a clapper or a ball drop in view of all cameras). Figure 2 shows the methodology employed by (Bot et al., 2019) when using a multi-camera array to scan and create and asset that captures the likeness of a turtle.

2.1.2 Cross polarisation and reflectance acquisition

VR is capable of simulating realistic lighting and accurate material properties. Reflectance acquisition techniques are used to measure an object's reflectance properties under varying lighting conditions. One such approach using polarisation techniques is outlined by figure 3, below. Numerous images are taken with different lighting conditions to sample the appearance of specular highlights under a dense sampling of lighting directions, which can be data-intensive and time-consuming, particularly when dealing with highly specular surfaces.



Set up dark background, polarised light source and subject. Calibrate camera with polarisation filter to minimise reflections

Capture **cross-polarised** image

Adjust the camera's polarisation filter, rotating it 90°

Capture **parallel-polarised** image

Adjust subject for differeny viewing angle

Repeat until capture is sufficient

Create 2 datasets: one of the **cross-polarised images** and one of the **parallel-polarised images**. Pair corresponding images by renaming the **parallel-polarised** image to be identical to its **cross-polarised** counter-part.

Open **parallel-polarised** image

Overlay the correspinding **cross-polarised** image

Edit *Layer Blend* to ***Subtract*** so that the **cross-polarised** layer is subtracted from the **parallel polarised** layer, necessary to calculate the light diffusion of the surface

Merge the layers by flattening the image

Desaturate the image, making it black and white

Save the file, overwriting the parallel-polarised image

Repeat until each parallel-polarised image has been converted into a **specular** image. It is possible to automate this workflow by creating a Photoshop Action (a macro).

Input **cross-polarised** images

Reconstruct mesh using **cross-polarised** images

Replace input images with **specular** images

Rebuild texture, creating a **specular map texture**

Export **3D mesh**, **cross-polarised texture**, and **specular texture**

Invert the **specular texture** to create a **roughness map texture**

Set the material of the 3D mesh to the **cross-polarised texture** which provides colour information

Within the material settings, set the roughness equal to the **roughness map** multiplied by a constant value (this value must be manually set to achieve accurate light diffusion)

Fig. 3 A flowchart showing an overview of the data processing required to prepare what information is collected in a cross-polarisation method (Frost et al., 2023) to acquire reflective data, including the software employed.

Cross polarisation methods produce an image where most of the specular data is removed using two orthogonal polarisation filters. One filter is placed on the camera lens, and the other is a polarising film positioned in front of the light source to illuminate the target with polarised light. Cross-polarised images are highly effective for photogrammetry reconstruction as they minimise disruptions caused by reflections (Frost et al., 2023).

The polarisation filter on the camera lens can be adjusted to be parallel rather than orthogonal, thus producing a corresponding image which preserves specular information. Subtracting the cross-polarised image from the parallel-polarised image yields a specular image. Collecting specular images from multiple camera positions allows us to create a specular map by replacing the cross-polarised data with the specular data during the reconstruction process. This map represents the reflectivity of the object's surface at different locations on the mesh. However, achieving this in uncontrolled environments, where ambient lighting is beyond our control or with large equipment that requires camera movement, can be challenging and result in inconsistencies.

2.1.3 Colour correction

To ensure the accuracy of the model texture, especially for its use in a games engine for simulation, managing lighting conditions is crucial. If lighting affects the color of the captured images, a Look-Up table (LUT) can be applied to the input images to correct their colour accuracy. Software like Houdini (SideFX, 2022) or Photoshop (Adobe, 2022) can generate this LUT from an image of a colour checker taken at the site under the same lighting conditions as the photos, and then batch process the input images, correcting colour information.

Most games engines have their own lighting systems. Depending on the 3D objects being rendered, most 3D games engines simulate realistic shadows for objects in relation to in-simulation light sources. These shadows can be dynamically calculated at runtime, adjusting with user interactions or object movements. In some cases, shadows might be baked into the scene if they are not expected to change. If shadows were captured in the source photos due to non-flat lighting during image capture, they could inadvertently become part of the object's texture information. To address this, the shadow information should be removed. This can be achieved by opening the texture data from the UV maps in software like Photoshop, where adjustments can be made to minimize or eliminate the shadows. This process homogenizes and evens out the lighting affecting the texture, allowing the games engine's lighting to handle shadows appropriately.

2.2 LiDAR

In recent decades, point clouds obtained through light detection and ranging (LiDAR) have become a significant data source for various mapping applications within the photogrammetry, remote sensing, and cultural heritage communities among many others (Leberl et al., 2010) (Wang et al., 2018). There are two primary LiDAR methods to consider, laser scanning and structured light scanning. Both make use of time-of-flight (ToF) calculations, the scanner can determine the distance and create a point cloud of the object's surface. Their advantages include their noninvasive nature, high precision, and interoperate easily with supporting software.

Aerial laser scanning (ALS) and Terrestrial laser scanning (TLS) are two examples of long-range scanning methods that rely on laser beam emission. The emitted lasers can reflect off of surfaces up to 130 meters away, and can be used to scan large objects such as airplanes. The Focus3D S120 (FARO) is a laser scanner employed by (Wang et al., 2019) as described in figure 5, so this method may be fit for our purposes, however, long-range can be more expensive and may require more time for data processing.

Structured light scanners project patterns of light (such as grids or stripes) onto the surface of an object. The deformation of these patterns on the object's surface is captured by the scanner's cameras. The distortion of the patterns is then used to calculate the 3D coordinates of the object's surface points. Cui, Tao and Zhao acknowledge that the 3D light-section reconstruction method (depicted in figure 4) is a common and applicable way to obtain point cloud data for the needs of 3D reconstruction potential accurate to the millimeter. Structured light scanners are generally faster than laser scanners and are well-suited for capturing medium-sized objects with moderate to high surface details.

However, like photogrammetric methods, structured light scanners struggle with reflective, transparent, or homogenous surfaces. Their accuracy can vary based on the complexity of the object's surface; for example the performance of these scanners suffers when there is a distinct lack of points of interest on the surface, as it makes it difficult for the algorithms within the software to accurately track the lasers position frame by frame. Consequently, the scanner will “slip,” leading to inaccuracies in scanning surfaces. We may mitigate some of these issues by scanning the surface multiple times, or by introducing additional features to aid 3D registration.

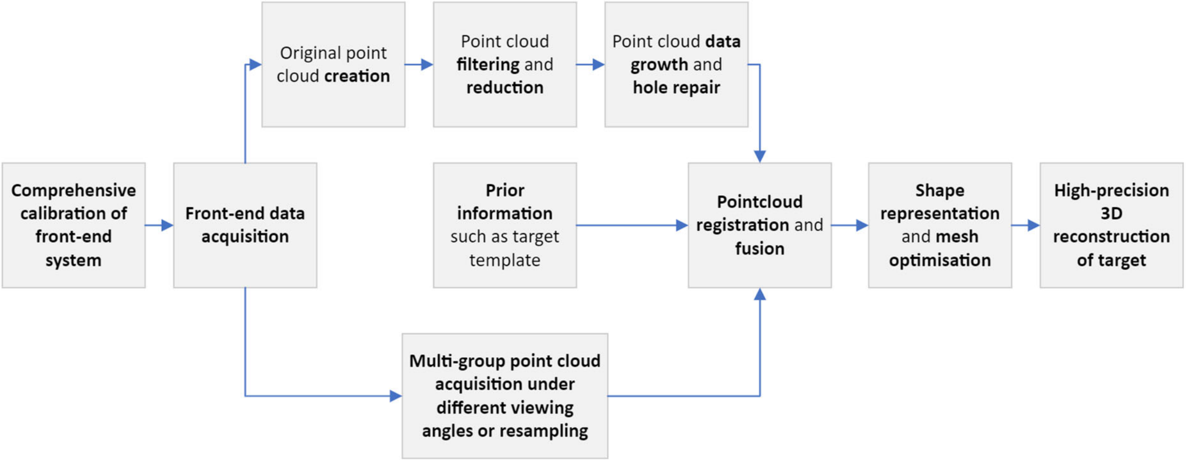


Fig. 4 A process diagram showing the light-section method for a structured light scan. (Cui et al., 2021)

2.3 Model Synthesis for Virtual Reality

To achieve realistic virtual representation, it's crucial to capture high-frequency details. However, this often results in high-polygon count 3D models generated by scanning methods, which can slow down real-time simulations, especially in virtual reality. Mesh decimation helps reduce the complexity by simplifying the mesh to a target polygon count, although some detail is lost in the process. As depicted in figure 2, in cases where the scan data has inconsistencies, further reconstruction and cleaning with 3D editing software might be necessary. Alternatively, the scan can serve as a reference for creating a new, more accurate mesh.

High-frequency detail can be restored by generating normal maps from the complex mesh, which are used to create detailed shadows and highlights. Unwrapping the mesh's topology into UVs is required to store this data as a texture file. Specialised software such as InstantMeshes as mentioned in (Bot et al., 2019) or similarly specific tools like those of Houdini (SideFX, 2022) called Sidefx Labs which contains the AutoUV as used in (Triantafyllou et al., 2022). After retopologising the mesh, any available texture information can be reprojected. If the captured

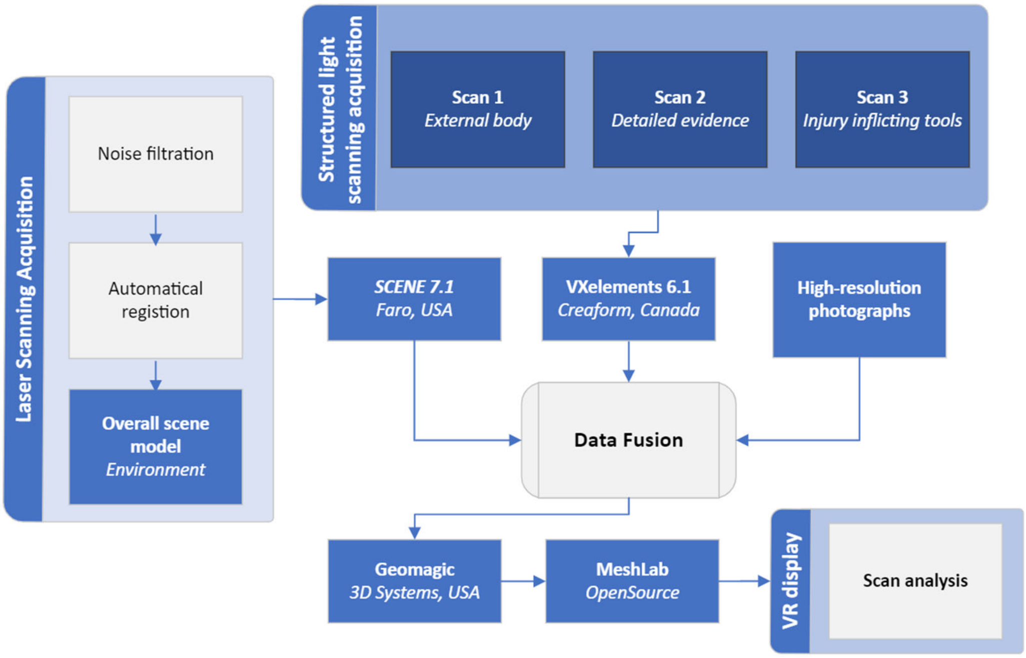


Fig. 5: A diagram showing an overview of methods being used to reconstruct a detailed environment for VR (Wang et al., 2019)

texture data is insufficient, libraries like Quixel Megascans provide high-quality textures for approximating the surface material.

One example (Alexander et al., 2009), involves the use of a stereo-camera rig with strategically placed lights. This rig is calibrated to capture multiple images simultaneously, each providing various lighting information: cross-polarized, parallel-polarized, and spectral line measurements for diffuse albedo, specular albedo, and 3D geometry, respectively. To aid data calibration, makeup dots on the target are used, ensuring they don't obstruct data while allowing precise realignment. By contrast. (Wang et al., 2019) merge laser scan point clouds using registration software. Ground control points (GCPs) and other scene features' known locations are used to combine scan data, creating a comprehensive indoor environment reconstruction. Additional scans made with structured light scanners add more detailed information to specific areas of interest for analysis.

Once the data from these various methods has been combined, the next key challenge lies in effectively separating these components to enable interaction within the virtual environment. Advanced VR interactions, characterized by direct manipulation, diverse input devices, and high degrees of freedom, demand the division of the unseparated scan-data model into distinct, potentially modular components. 3D modeling software will play a pivotal role in separating the components for independent simulation of their interactions.

For training purposes, equipment behaviors will also require virtual recreation. While the best approach is to have firsthand expert demonstrations of the equipment, this is often not feasible due to factors like high risks and limited accessibility. In such situations, an alternative approach is to attach recording equipment to a professional who can perform the necessary operations. This recorded footage can then be used as a reference for replicating the equipment's behavior in a virtual environment.

3. TECHNOLOGY

A standard asset creation pipeline involving scanning processes will require several pieces of hardware to collect data, with the appropriate software to process the information. We will also consider hardware and software required to develop functionality and render the equipment as interactable models within a VTE. The most effective solutions will be discussed below.

3.1 Software

Each step in this process necessitates specific software tools. Initially, images must be prepared for alignment, followed by running photogrammetry algorithms to construct textured models from these images. The subsequent phase involves processing the data obtained through 3D scanning to create a 3D model that faithfully represents the physical geometry of the scanned subject. This model must be optimized for seamless integration into a games engine for virtual interaction, and various texturing solutions will be evaluated. It's common to encounter multiple software options for each stage of the scanning process. Some software packages bundle applications to be used in tandem with diverse workflows, and open-source alternatives may also be available. (see Table 1). For the software upcoming to be listed, the minimum processing requirements would be a 2GHz CPU and 16GB or more RAM.

Table 1. Depicts a selection of software available from the Geomagic application suite, and corresponding open-source applications

Geomagic software	Description	Open-source alternative
Geomagic Capture	Scanner specific registration software	
Geomagic Design X	Rebuild CAD data reverse engineered from scans	OpenCAD
Geomagic Control X	Visualising and analysing data for quality control	Volume Graphics
Geomagic Freeform	Manipulate and manage large unstructured meshes	MeshLab

3.1.1 3D scanning software for 3D scanners

To process the results of the scanning process, various specialized software solutions are employed to manage scan data and enhance scenes. For this type of 3D scanning software, it's often bundled with 3D scanning hardware, and many developers have created their own software packages to accompany their laser scanners. Faro utilizes Faro Scene for scan registration and cleanup of collected geometry data, whilst Faro Zone 3D is used for tasks like importing high-res photos, utilizing registration targets, and performing metrics calculations within 3D reconstructions (Wang et al., 2019). Creaform's VX Elements is used to calibrate data collected from structured light scanners, while VX Model serves for more detailed scene modeling or measurements. Artec offers a comprehensive set of tools within Artec Studio, tailored for scan reconstruction and will be suitable for processing scan data. Additionally, CloudCompare (Open source) is an open-source solution that allows us to compare and edit point clouds or meshes (Dewez et al., 2016). It provides the capability to transform scan data to ensure alignment with our photogrammetry reconstructions.

3.1.2 Photogrammetry software

RealityCapture is renowned as one of the top choices for photogrammetric reconstruction for speed, accuracy, and format compatibility. Due to its exceptional capabilities, it is available at a premium price point. Other popular premium software includes Metashape (Agisoft) and Recap Pro (Autodesk).

There are many free photogrammetry software, the most popular of which includes Meshroom (AliceVision) which has been integrated as a free plug-in for 3D processing software such as Houdini (SideFX) and Maya (Autodesk). Other open source solutions include 3DF Zephyr, Colmap, and Regard3D.

3.1.3 3D mesh processing/modelling

3D mesh processing is a fundamental component of the 3D scanning and modeling pipeline, used to manipulate, refine, and optimize the three-dimensional mesh models generated from various data acquisition methods, such as laser scanning and photogrammetry. Most have access to various plug-ins which augment and enhance the capabilities of the software, unlocking a multitude of functionalities that cater to diverse project requirements.

Premium solutions include 3DS Max, Maya (both Autodesk), Houdini (SideFX), and ZBrush. Zbrush is well known in the professional industry for its many highly advanced tools for tasks like cleaning, healing, and texturing. 3DS Max offers cloth, light and liquid simulations and its own scripting language (MAXScript). Houdini's procedural modeling solutions may provide scalability of modular components, enhancing the flexibility and efficiency of the asset creation and simulation process.

Blender is a remarkable free and open-source 3D modeling software known for its exceptional versatility. It offers a wide spectrum of capabilities, making it a powerful tool for cleaning up scans and repairing meshes. While Blender has a learning curve, due to its wide availability, there is a wealth of learning resources online for techniques such as hard surface modelling. There are also plug-ins which allow you to create highly detailed materials, like Substance Designer (Adobe), or create powerful renders of 3D objects. For tasks like modelling switchgear equipment, Blender's extensive features make it an ideal choice for this purpose.

Among other open-source solutions are weaker options such as Autodesk TinkerCAD and Vectary. These free tools operate directly in your web browser, however, are primarily designed to educate entry-level users. For instance, TinkerCAD is often integrated into 3D printing processes and has limitations, such as restricting OBJ uploads to models with up to 300,000 faces.

More open-source options include OpenSCAD, FreeCAD, and Sculptris: OpenSCAD requires a bit of previous skill as you have to code your objects and it works with primitive geometric shapes and reads the code to modify and render them creating 3D models a with constructive solid geometry (CSG) which can be beneficial when it comes to 3D printing your projects. FreeCAD is a 3D modeling software was based on Python language which allows you to add new specialized features. Similarly Sculptris modifies pre-existing shapes with brushes of different strokes.

3.1.4 Games Engines

Lastly, the software we must consider is running the simulation so that it may be viewed and interacted with by a VR user. Unreal Engine 5 (Epic Games) natively supports VR development and also has the Quixel Bridge feature, giving easy access to tools and resources which may be beneficial or time saving for to the project, saving development labour. Similar plug-ins are available for Unity and the open-source Godot Engine. These games engines provide the necessary framework for creating immersive and interactive virtual environments based on the 3D models and assets generated during the scanning and modeling process.

3.2 Hardware

Hardware plays a significant role in capturing visual data and running the software necessary for asset visualization. To achieve accurate photogrammetric reconstruction, the quality of the captured images is essential, motivating us to explore several camera options, including the Mattterport Pro, DSLR cameras, and due to their wide availability we will also consider mobile phone cameras. For highly accurate metrology of our scanning targets, we shall review Lidar and structured light scanners. Lastly, we will address hardware that may be used to provide user interaction within a virtual environment, such as head mounted displays (HMDs) and review processing requirements.

3.2.1 Cameras and registration

Standard photographic equipment is often more accessible and cost-effective compared to other 3D scanning methods like LiDAR or structured light scanning. The camera will be used to gather input images to create a 3D model from photogrammetry with an accompanying texture. When aiming for the greatest accuracy, images with a higher resolution are preferred, therefore, to opt for a camera of superior quality is justified.

Various cameras may differ in quality, varying in number of pixels, sensor size, and field of view. Many pixels help to boost the image resolution to capture fine detail, most noticeable when zoomed in. Different lenses can be used with different DSLRs to correctly calibrate the cameras for scanning purposes. Conversely, smartphones may not have as many customisable options or similar fine-controls over the image capturing process, however as can be inferred from table 2, smartphones can often offer sufficiently high-quality visual data, as well as being widely available, highly portable and very accessible. Some smartphones have a single camera, others have dual sensors, quad sensors, however, frequently, high-megapixel cameras being used on market smartphones don’t output photos as high as the camera is capable of because of pixel-binning.

Using a camera will be essential to capture texture and colour detail, as well as for providing proper reference for registration within the 3D processing software.

Table 2. Comparing the Megapixel value of various available camera devices.

Device		Megapixels
Mobile Phone	iPhone 14 Pro Max	48MP
		12MP
		12MP
	iPhone 11	12MP
		12MP
	iPhone 6	8MP
	Samsung Galaxy Fold 5G	16MP
	Google Pixel 7	50MP
DSLR Camera	Nikon D3300	24MP
	Cannon EOS ID Mark III	2.11MP
	Sony X7R	61MP

3.2.2 LiDAR Scanners

Table 3. Illustrating the range in available LiDAR scanners depending on the required range of the scan.

Manufacturer	Short range	Medium Range	Long Range
Artec	Micro Space Spider	Eva Lite Eva Leo	Ray II
Faro	Gage FaroArm	Freestyle Vantage	Focus
Creaform	R-series	Go!Scan HandyScan MetraScan	MaxSHOT 3D
Sick		S300 series Tim-S	OutdoorScan 3
Leica		BLK 360	RTC 360 Scanstation

LiDAR scanners are known for their high accuracy and ability to capture intricate details. For the purposes of this project, they will be used for capturing complex geometries and surfaces with varying textures. Different scanners with different features are better suited to various scanning tasks depending on the object size and the necessary scan quality. Faro are well known for their mid-long-range scanners, and Creaform have also been used for their handheld scanners by similar project. Other scanners include the Geomagic capture and capture mini, ideal for “desktop scanning” of small objects up to the size of a shoebox, as well as the EinScan product range from Shining3D.

Certain scanners integrate both camera components and structured-light sensors. This grants the scanners the ability to gather supplementary colour information, which is particularly valuable for laser position-tracking and registration processes. Some artec scanners include cameras, allowing colours that the texture camera has captured to the 3D mesh being created. The quality of this texture is sufficient for a majority of metronomic applications. The quality depends of the generated geometry depends on the selection of the scanner, on the scanning distance, the lighting conditions, and the general execution of the scanning routine.

3.2.3 Matterport

Matterport is a company specializing in 3D scanning technology and software to capture and render 3D models of physical spaces. Their Matterport Pro Camera utilizes depth-sensing cameras and imaging sensors to create 3D point clouds of environments. The Matterport Pro2 3D camera offers 36MP images with a scan accuracy of +/- 50mm, while the Pro3 improves accuracy to +/- 20mm at a 10m distance. This tripod-mounted device captures comprehensive visual data by rotating 360 degrees in a short time. However, there are privacy concerns regarding detailed models unintentionally capturing sensitive information.

Matterport provides an iPad app for camera control, offering a "Dollhouse" view to identify unscanned areas. Users can navigate 3D models by selecting points within the model, making it popular for virtual property or office tours. They also have a mobile application using LiDAR sensors in phones to scan objects and generate 3D meshes in .obj format. While convenient, these scans may lack the precision needed for high-fidelity virtual assets, particularly in capturing intricate surface details.

For this project, Matterport services have drawbacks. They can be costly due to hardware expenses, service charges, and the need for additional payment to access the metadata folder (MatterPak). The generated point cloud format (.xyz) lacks widespread compatibility, often requiring conversion to more universally accepted formats like .e57. Furthermore, Matterport's scanning technology might not provide the required accuracy and detail for the project, especially in capturing nuanced surface features necessary for high-fidelity 3D models.

3.2.4 VR Hardware

Different head-mounted displays have been designed for slightly different purposes. While most headsets come with controllers, not all controllers are the same. Because the head-mounted display is the hardware through which the student interfaces with the training environment, the controller will dictate the possible depth of interaction In the context of this research, the emphasis is on a cost-effective and immersive VR solution. Many VR headsets can run the proposed simulation. However, a mid-range specification HMD with stand-alone capabilities is preferred over more powerful and expensive headsets such as the HTC Vive Pro line of HMDs. This choice imposes certain technological limitations on the performance of the 3D virtual representation.

For this project, the target headset will be a Meta Quest 2 VR headset. As well as its performance capabilities, the oculus link cable accessory allows the HMD to interface easily with a PC for development and testing purposes. The Pico Neo line of HMDs boasts similar specifications as the Meta Quest 2, both headsets have previously been used for virtual training and education purposes (Cowie & Alizadeh, 2022; Han et al., 2022; Moolman et al., 2022).

4. EXEMPLIFYING THE FRAMEWORK: HIGH-VOLTAGE ELECTRICAL SWITCHGEAR

Photogrammetry excels in capturing high-detail visual information, although as mentioned the resulting three-dimensional information may be susceptible to gaps, noise and inaccuracies. To use a fixed-camera or a multicamera set-up is feasible only for objects compatible with the rig in scale and shape, meaning they are mostly applicable only for small-to-medium objects. We shall be capturing objects on the site of their professional environment, therefore lighting conditions may not be perfect. Because of this the geometry that will result from our photogrammetry effort will likely have inconsistencies and not be very robust. For this reason we shall not rely on geometry data obtained this way, however, efforts will be made to retain any worthwhile texture information generated by the photoscan.

The 3D geometry obtained from LiDAR scan will likely be more robust however due to poor exercise of control over the lighting conditions, a complete and consistent scan cannot be guaranteed. As mentioned in section 2, we shall seek to mitigate these inconsistencies by employing the light-section method and performing multiple overlapping scans. To avoid incongruities caused by erroneous position tracking, a consequence of featureless scanning geometry, one solution emerged as notably effective: affixing ping pong balls or golf balls onto the surfaces of the equipment using blue tack. This addition of texture intricacies facilitated a more precise registration of the scanner's position during the scanning process. As the scanner traversed the modified surfaces, the intricate texture details provided the necessary points of reference for the algorithms to accurately determine the scanner's movement. Consequently, the scanner's accuracy improved significantly, and the issues of slippage and positional loss were effectively mitigated.

After combining the LiDAR and photogrammetry data into a unified 3D visualization, we suggest employing Blender to refine and optimize this asset. In case the resulting asset falls short of the realism required for real-time VR, the reconstructed data will serve as a reference template for generating a new mesh. By utilizing the scan data as a guide, the precise measurements obtained from the scan data can inform the development of an equally accurate 3D object. Furthermore, we have access to suitable replacement textures to maintain our goal of photorealism. While this process may demand additional time and effort, it is essential for achieving an immersive virtual reality experience.

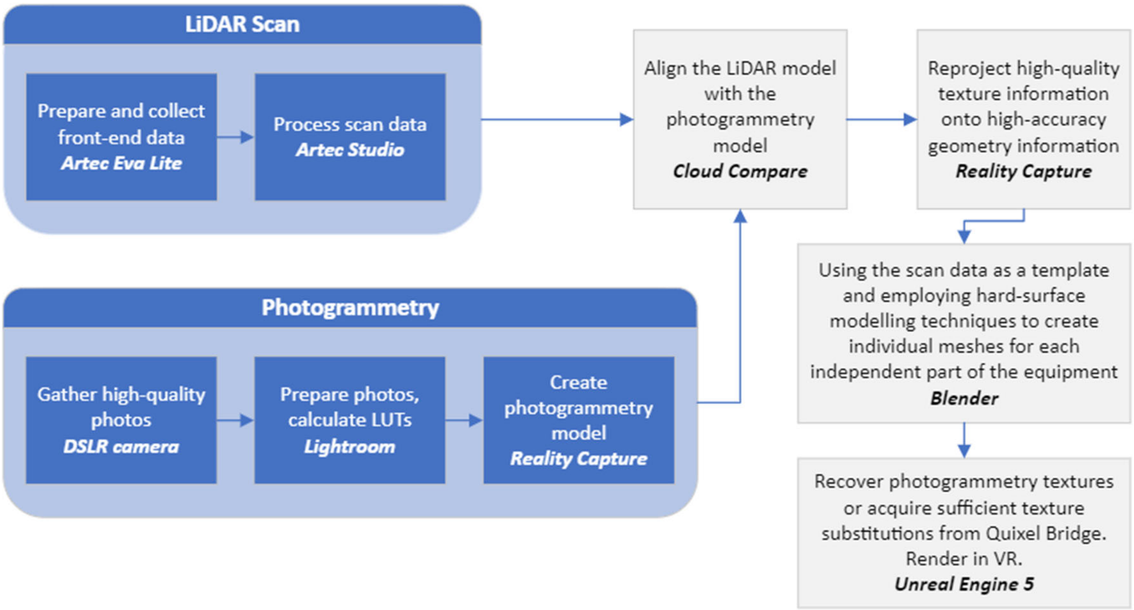


Fig 6:. Shows a process diagram outlining the methodology best suited to meet our needs of reconstructing a piece of equipment for virtual representation

5. CONCLUSION

This paper is structured to detail the methodological approach used in each stage, its limitations, and to empirically evaluate its effectiveness. By integrating advanced technologies and methodologies, this research strives to simplify the development of immersive training environments by reviewing and optimising the process of virtual representation. The framework presented is designed to methodically overcome various challenges, highlighting opportunities for automation of repetitious tasks associated with the necessary data processing, and facilitating a smooth shift from physical equipment to the production of highly lifelike virtual training environments.

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