Low-Complexity Workflow for Digitizing Real-World Structures for Use in VR-Based Personnel Training

Mason Smith(✉), Andre Thomas, Kerrigan Gibbs, and Christopher Morrison

Learning Interactive Visualization Experience (LIVE) Lab, Texas A&M University,
College Station, TX 77843, USA
`{masonsmith,cmorr}@tamu.edu, manink@arch.tamu.edu,`
`klg2799@email.tamu.edu`

Abstract. Since the advent of virtual reality (VR), there has existed a need for digital assets to populate virtual environments. Virtual training scenarios have risen in popularity in recent years, increasing the need for digital environments resembling real-world structures. However, established techniques for digitizing real-world structures as VR-ready 3D assets are often expensive, complicated to implement, and offer little to no customization/ To address these problems, a "low-complexity" digitization workflow adapted from existing research and based on procedural modeling is proposed. Procedural modeling allows for non-destructive customization and control over the digital asset throughout the front end of the digitization workflow. A real-world VR training project using this workflow is outlined, demonstrating its advantages over other established digitization techniques.

Keywords: Virtual reality · Procedural modeling · Digitization

1 Introduction

1.1 Virtual Environments and VR-Based Personnel Training

Virtual Reality (VR) is an immersive human-computer interface by which humans can interact with simulated digital environments [5]. In the last decade, VR has risen in popularity as a training platform for various industries, such as construction, oil and gas, law enforcement, and military [20, 27]. Regardless of industry, VR has become increasingly popular as a solution for job safety training and also highly specialized tasks for workers.

The advantages of conducting personnel training in VR are manifold: Bringing a trainee into VR can be easier than taking them to a physical job site or training area. A virtual environment not grounded in the physical world allows the trainee to make mistakes without bringing harm to job equipment, themselves, or others [13]. The interactive nature of virtual environments makes it possible to iterate through or repeat tasks, instantly resetting equipment with a few lines of code.

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Despite its many advantages, VR training applications are still not widely used in some industries. Existing research suggests that an environment's poor graphical quality may hinder the perceived usefulness of VR training applications [6]. In their critical review, Li et al. [19] cite the detail level of job-related digital assets as a potential barrier for accepting VR-mediated training environments. Inaccuracies may lead to "visual discomfort and incorrect geometry perception" and may discourage the use of VR training in industrial settings according to Segura et al. [25].

These findings show that one of the most significant issues in VR training development is how to create job-related digital assets (buildings, structures, equipment) accurately and efficiently. Digitization is the technique by which real-world objects are represented virtually as objects made up of computer code. Because of the highly-specialized and proprietary equipment often used by individual companies, existing repositories of 3D assets are unlikely to include the needed job-related 3D assets for a given VR-mediated training scenario. Companies often update their equipment as technology advances, compounding the need for customizable job-related 3D assets. Therefore, for the purposes of VR training, digitized assets must be accurately represented, be created quickly, possess a high level of detail, and allow for easy customization. This will allow for training scenarios that can be iterated easily as training needs change and real-world equipment are updated.

There exist several techniques for digitizing real-world objects and structures for VR. However, many of these techniques are expensive, time-consuming, require specialized training, and result in assets that are not easily modified at the model level nor easily compatible with VR.

The overall goal of the proposed methodology is to address the questions of customization and complexity when digitizing real-world objects for VR. We propose a hybrid "low-complexity" workflow for digitizing complex industrial structures using procedural modeling. This method relies on image-based reference rather than expensive point cloud data. Using procedural modeling allows us to recreate 3D assets with a high level of detail. The parametric design of procedural-modeling allows for assets that are easily iterated and modified according to the needs of the training scenario. Ultimately, this method is highly suitable for the modular nature of real-world industrial structures and equipment. We aim to present this workflow as an alternative to current widely-used digitization techniques.

Using procedural modeling as its real-world object digitization technique of choice, this research seeks to answer the following questions: How effectively can procedural modeling be used to digitize complex and large-scale industrial structures for VR training? To what extent does procedural modeling address the challenges present in other existing digitization techniques for VR training?

Real-world object digitization for VR is currently being used in several industries, including construction, engineering, oil and gas, city planning, architecture, archaeology, and education. Digital assets based on real-world objects are used not only for training but for heritage conservation, building information modeling (BIM), urban planning, and ecology. Varying asset digitization techniques for each of these purposes exist with varying results. In the following section, real-world object digitization techniques will be outlined.

2 Real-World Object Digitization Techniques

2.1 Photogrammetry and Laser Scanning

Photogrammetry remains one of the most popular and developed techniques for digitizing real-world objects. Photogrammetry involves acquiring several images of a real-world object from several angles. These flat images are interpreted as 3D views of the object when combined by a specialized software. The more comprehensive the image acquisition, the fewer data gaps there will be in the interpreted 3D model. Via photogrammetry, it is possible to “bake” the surface texture and lighting qualities of the real-world object into the digital object. Laser scanning is a similar technique whereby lasers scan objects or environments creating datasets (dubbed “point clouds”) of varying resolutions. The point cloud data set may be interpreted and reconstructed as a 3D mesh, similar to photogrammetry [21]. Both techniques have been used to digitize real-world structures with a high degree of structural and surface detail. For example, scanning electron microscopy was used to create 3D representations of Cu-Zn-Al catalytic pellets. A single 3D mesh was made up of 180,000 facets [14].

Achakir, et al. [1], in their paper describing the digitization of the Hassan mosque, presented three criteria for appraising photogrammetrical digitizations and laser point clouds: completeness, resolution, and accuracy. The pursuit of maximizing these criteria has driven much of the recent innovations in photogrammetry/laser scanning.

Besides acquiring images on foot, researchers have experimented with using unmanned aerial vehicles (UAVs) or aerial drones to improve the completeness and accuracy of the resulting data set. Cappelletti used UAVs to carry out forensic scans of engineering sites, arguing that UAVs can accomplish the task much faster than grounded personnel [5]. Dugdale, et al. [9] applied the drone-based method to scan a forest canopy, taking advantage of the resulting 3D models’ baked shadow information to study temperature models. Drones were used to non-invasively identify and digitize whales in a 2019 ecological study [15]. UAVs were also used to make 3D maps of urban areas for the purposes of urban disaster planning [16]. Apart from UAV-based image acquisition, researchers have discovered other novel methods for scanning real-world objects, for example using the Microsoft Hololens [4] as a lower-cost alternative to drones or ground-based robots [17].

Existing research has revealed the many caveats and challenges surrounding photogrammetry and laser point cloud scanning. Photogrammetry and laser scanning are often considered to be high-cost, cumbersome processes that take a lot of processing time [8]. Ahmed et al. [2] found photogrammetry and laser scanning too sensitive and costly for the purposes of their heritage preservation project. They also pointed out that highly specialized technology for photogrammetry and laser scanning constitutes a “black box” that lacks accessibility. For Cappelletti et al.’s forensic engineering research, UAV-based image acquisition was most effective when the UAVs travelled in a circular flight plan around the real-world subject [5]. However, circular flight paths might not always be possible. Furthermore, baked texture and shadow information might lead to an unclear or unreadable image if the weather at the time of scanning creates high-contrast shadows. In the case of Kucharczyk et al.’s pre-disaster mapping project [16], significant gaps in the UAV-acquired source images created distorted and inaccurate 3D models. A 2017 study [28] found that harsh real-world environments (for example environments with high levels of vibration), complicate photogrammetry or laser scanning efforts. In the case of the aforementioned research on digitizing catalytic pellets, the photogrammetric technique was useful for capturing the miniscule detail of the pellet components, but not for real-time virtual environments [14]. Indeed, high-resolution 3D meshes are not optimal for 3D VR/AR applications where maintaining an optimal frame rate is crucial to the user experience.

2.2 Manual 3D Modeling

Another common technique for digitizing real-world objects is to manually create the 3D models using flat images as reference. For this technique, the vertex, edge, and face components of a static 3D mesh are manipulated interactively to re-create the shape of the real-world object in question. This is carried out in an interactive 3D graphics software package such as Adobe 3ds Max or Autodesk Maya. This technique is often utilized when assets' geometry need to be optimized for real-time VR/AR applications. For example, Ahmed et al. [2] modeled heritage site structures in 3ds Max, using thousands of acquired images for reference. Poloprutskya et al. [23] adopted a similar image-based approach. Denker and Ahmet [7] developed a virtual recreation of ancient Palmyra, drawing from reference images, drawings, fine art works, and text descriptions. However, a lack of color photographs and incomplete reference descriptions made specifying texture, color, and light information challenging. Osanlou et al. [22] used 3D modeling software to re-create ancient Chinese ceramic artifacts, using their best judgment to create digital assets that resembled the real-world artifacts. However, this technique does not afford the specificity required to bring highly-detailed objects into the digital realm.

2.3 Hybrid Techniques

To avoid some of these challenges, some researchers have adopted hybrid approaches to real-world object digitization, combining photogrammetry and manual 3D modeling [12]. These approaches include "cleaning up" high-density photogrammetry-based meshes or using photogrammetric meshes alongside manually built ones. A 2017 paper on virtually re-creating the Augusteum of ancient Herculaneum mentioned how researchers produced a more VR-friendly 3D model by using 3D software to reduce a 5-million-face mesh to around 20 thousand faces [11]. Manferdini et al.'s project [21] on reconstructing a defaced Roman statue of Nero used a high-density laser-scanned mesh of the remaining sculpture fragments as a basis for reconstructing the statue's form as it may have once stood. In the case of the long-lost Nero statue, existing images, records, and artifacts were used alongside the scanned point cloud as reference for the final result.

These hybrid techniques combining photogrammetry/laser scanning with manual 3D modeling are not without their challenges. Consider Dylla et al.'s "Rome Reborn 2.0" project [10], an attempt to virtually reconstruct the city of Rome as it existed in antiquity. The Rome Reborn 2.0 team used a hybridized digitization technique which involved photogrammetry/scanning of existing buildings, manual 3D modeling, and procedural/parametric modeling. The team's procedural approach involved parametric modeling grammars which were informed by "the well-described rules of Classical architecture". By adopting a hybrid methodology, they were able to reduce the original Rome Reborn 1.0 environment, made up of about 400 million polygons, to a more manageable 9 million polygons. However, the team discovered that details of the scanned structures (such as windows or doors) came from the baked textures of the scanned meshes and did not exist in the mesh's actual geometry. This led to the scanned structures clashing aesthetically with the manually-modeled and procedurally-generated structures. Indeed, Dore et al. [8] state that any digitization process which includes manual 3D modeling or clean-up of assets remains a time-consuming process.

2.4 Parametric/Procedural Modeling

Parametric modeling is an emergent digitization technique where the configuration of a 3D asset is controlled by intrinsic parameters representing physical properties. VR developers have used pre-built parametric CAD models for virtual industrial training [26] and building information modeling (BIM). Dore, et al. [8] suggested procedural modeling as an alternative for BIM-focused parametric CAD modeling. Procedural modeling is an automatic, highly flexible 3D asset digitization technique wherein the attributes of the asset are directly controllable via code. Procedural modeling applications such as Houdini by SideFX allow the 3D artist to interactively create procedural objects and effects, organizing attribute code into nodes.

Procedural modeling avoids the imprecision of manually modeling assets by hand; procedural assets' attributes may be controlled by simulated physics via code. The high level of control inherent to this technique allows 3D artists to optimize asset geometry for VR, potentially avoiding the extraneous vertex count of 3D point cloud data or CAD models. Procedural modeling applications may import diagrams, blueprints, and CAD models for reference, allowing the 3D artist to recreate real-world objects on-spec. The modular code-based configuration of procedural models allows for them to be modified and updated as real-world objects and equipment are updated. Their node-based organization allows 3D artists to flexibly modify the digital assets as needed, re-importing them into the VR development pipeline. Dore et al. [8] described procedural modeling as a possible alternative to traditional parametric modeling techniques used in BIM (Building Information Modeling) because of its high potential for automation and flexible code-based design.

3 Methodology

3.1 The "Low-Complexity Method"

A 2018 paper by Li, et al. [18] described a "low-complexity method" for digitizing hydroelectric generating equipment for a virtual training scenario. The researchers decomposed the needed assets into sets of parts and components as an application of object-oriented thinking. Essential equipment components were digitized and then instantiated as "prefabs" in the Unity game engine to avoid redundancy. By breaking the digitized hydroelectric equipment down into smaller components, the simulation could be easily updated as real-world equipment parts may be updated. They used collected images and

CAD/CAE drawings as specifications for how to create the digital assets. Shaders were used to approximate materials inside the virtual training engine, allowing for further customization and iteration as needed. The result was an efficient asset digitization methodology that allowed for a high degree of customization absent in photogrammetry/laser scanning.

This research proposes a similar workflow to the aforementioned "low-complexity method" to digitize complex job-related equipments and structures. However, while Li et al.'s methodology does not describe exactly how the hydroelectric equipment was digitized into 3D models, ours uses procedural modeling to provide a further level of customization. Here, an outline of the proposed methodology as well as our existing preliminary work will be presented.

Our proposed methodology for efficiently digitizing real-world complex industrial equipment and environments is summarized in Fig. 1. The steps of asset modularization, shader definitions, modular component modeling, and virtual scene creation represent the front-end steps of the workflow. It is in the front-end that most of the customization of the 3D asset occurs. To explain these steps, we will reference an existing VR training project in which a dairy cow milking machine was digitized for virtual reality by a technical artist in the LIVE Lab at Texas A&M University.

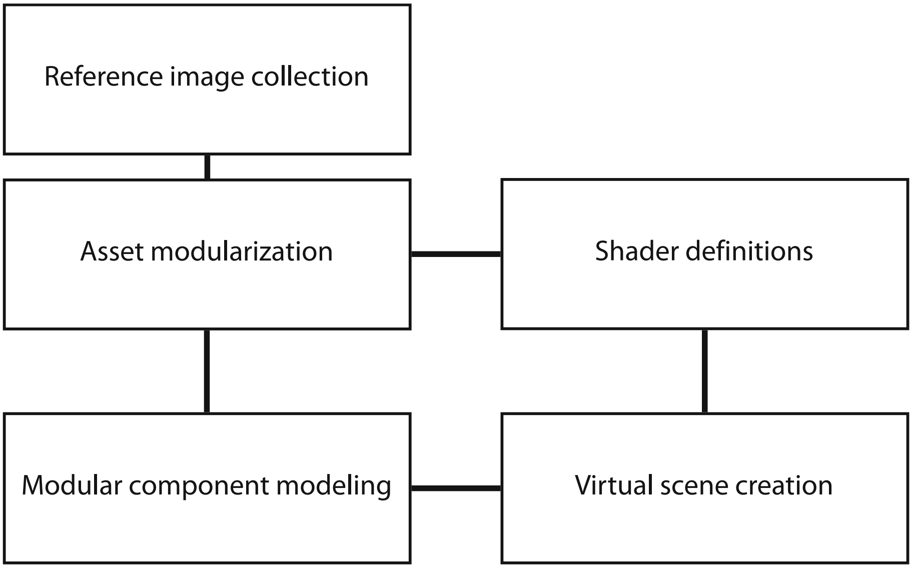

Fig. 1. "Low-complexity" methodology for digitizing complex industrial equipment and structures for use in virtual environments. Lines represent the flow of asset customization between steps in the workflow, front-end and otherwise.

3.2 Reference Image Collection

Researchers were led on a tour of a dairy farming facility near Dallas, Texas, USA and took various photographs of the milking machine. 39 photographs and videos were retained for reference purposes (see Fig. 2). The images included various angles around the milking machine at various levels of closeness to the equipment. They also include images of the machine being occupied by cows and unoccupied. Photographing the milk machine took about an hour.

While the accuracy of photogrammetry is dependent on the comprehensiveness of the image capture, our workflow does not require such comprehensiveness. Here, the goal is to simply capture as few or as many photographs as needed for the digital artist(s) to analyze the appearance and basic operation of the job-related equipment. Acquired photographs may have different levels of exposure from each other or zoom in on a particular component in detail. Unlike photogrammetry, which uses image acquisition as a method for data input, the proposed workflow uses image collection for the benefit of reference and analysis, with photographs being able to be combined with CAD drawings, blueprints, and other technical images to increase understanding of the job-related equipment.

Fig. 2. Example of a collected image for the milking machine project.

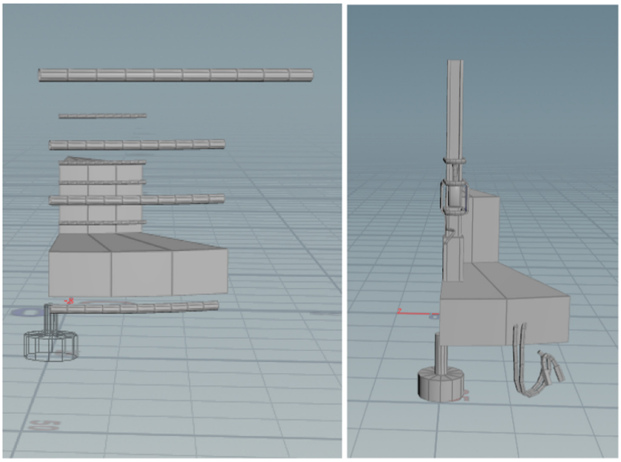

Fig. 3. Procedurally generated milking machine components.

3.3 Asset Modularization and Component Modeling

The technical artist studied the photographs, analyzed the structure of the milking machine, and made determinations on how to break the entire structure down into modular components. Because the machine has a circular structure and is made up of twelve evenly-spaced milking bays, the technical artist determined that only one twelfth of the entire structure needed to be created in 3D. The remaining parts of the structure could be instantiated in the virtual reality engine during the scene creation step.

The components of the milking machine were then modeled procedurally in Houdini by SideFX (see Fig. 3). Houdini allows for nodes, representing chunks of 3D graphics code, to be defined and interconnected to make up a single parameterized object. Changes to the parameters of a single node may affect the appearance of the whole asset. Thus, a high level of customization is achieved for iterative design. The complete 3D model took 13 h and is made up of 16,000 polygonal faces.

3.4 Shader Definitions

Because the milk machine was part of a preliminary experiment, asset textures were achieved with predefined shaders in Substance Painter by Adobe (see Fig. 4). Ideally, these shaders would also be created procedurally to retain the high customization we seek. Texturing the assets using procedural shaders allows technical artists to update or adapt the textures to preferred levels of realism more easily than with baked textures which are not as customizable.

3.5 Virtual Scene Creation

Finally, the many digital assets are imported and assembled in a virtual scene. This may be accomplished in a real-time game engine such as Unreal or Unity. The "low-complexity method" is useful here, because any individual asset may be imported as a

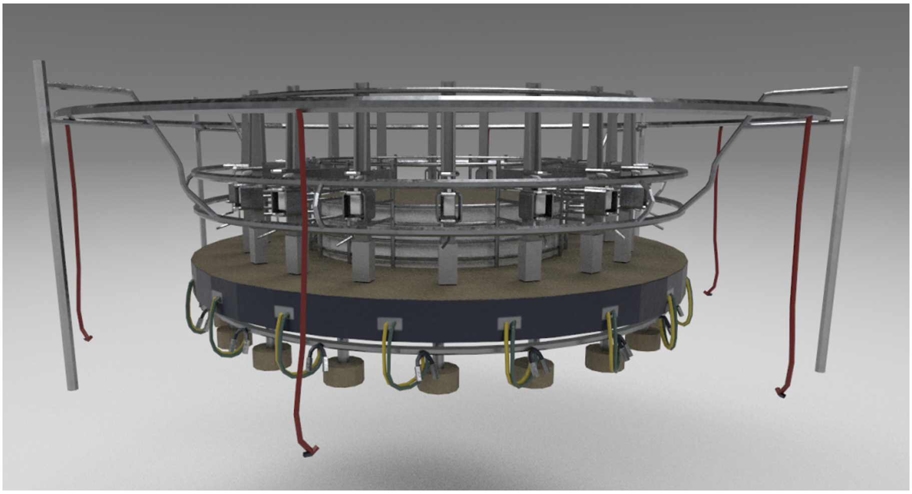

Fig. 4. The complete procedurally-generated milking machine asset with textures.

separate scene object. This allows for complex structures to be constructed out of their smaller components while allowing each component to be modified and re-imported in a way that is non-destructive to the whole virtual environment pipeline. Shaders for texturing 3D assets may also be treated this way. Real-time lighting, easily modified and iterated upon, is also accessible in game engines. Game engines are also useful for rapidly and interactively testing the scene and its objects to suit the needs of the virtual environment.

Once the virtual scene is assembled, it may be manipulated via code to make the digital environment interactive. This interactivity would reflect the functionality of the job-related equipment according to their design and the requirements of the training scenario.

4 Discussion

The proposed methodology for real-world object digitization uses procedural modeling as its technical basis. This methodology is justified by the advantages of using procedural modeling over other techniques such as photogrammetry or manual vertex-based modeling. Procedural modeling allows for a higher level of customization absent from other techniques. Artists creating procedural models may avoid the implicit vertex density and baked light interaction of objects scanned via photogrammetry. The physical appearance and other attributes of a procedurally-modeled 3D object may be parameterized and customized via code. Therefore, the creator of the procedurally generated 3D asset has greater control over the production of the asset. This high level of customization suits the iterative nature of interactive design.

One of the advantages of VR-assisted personnel training is the simulation of functioning job-related equipment. Procedural modeling's ability to organize real-world equipment and structures into groups of individual digital objects allows those objects to be given simulated functionality via computer code. While CAD models of job-related equipment may be available, it is unknown if their object hierarchy is organized in a way that allows for such functionality. For example, a digitized lever on a CAD model may not be able to rotate about its fulcrum without breaking the entire CAD model down in a 3D modeling application, isolating the vertices, edges, and faces that make up the lever, defining a separate object from them, defining the object's rotation axis to be at the lever's fulcrum, and re-exporting the entire CAD model with the new changes. However, using procedural modeling, the lever and its fulcrum may be defined as its own individual object within the hierarchy of the digitized equipment. Later, when imported into the digital scene, the lever may be animated or given functionality via computer code.

The adapted "low-complexity" approach also lends itself well to the specialized nature of development workflows used by creative studios. From a production standpoint, the flow of non-destructive customization in the front-end of the proposed workflow is highly compatible with the typical studio structure of specialized workers who take charge of each step of the 3D asset creation process i.e. modeling, texturing, lighting, virtual scene assembly, and interaction programming. Any time a job-related 3D asset needs to be updated to reflect changes to the real-world equipment, individual steps of the workflow may be identified for implementing the changes without having to restart the entire digitization process. Specialized workers may then be brought in to the development pipeline as needed. In contrast, a photogrammetric model of job-related equipment would have to undergo costly and time-consuming re-scanning if the 3D model needed to be updated. A procedural modeling-based, low-complexity workflow is advantageous for VR production teams because of its high potential for compartmentalized development steps as the current global COVID-19 pandemic forces more and more businesses to work remotely.

However, this methodology is not without its weakness. The most significant potential weakness may be that of scalability. While our milking machine asset took roughly 16 h for a small team of technical artists to digitize, it is not known how long it would take to digitize an even more complex structure such as an oil platform. At a higher scale, this workflow or parts of it may prove less efficient than other methods. For example, our workflow uses an image-based approach as reference for the real-world objects to be digitized. While the task of photographing the milking machine was logistically simple, gathering images for a larger, more complex structure may prove more difficult. Furthermore, some structures such as oil platforms may be situated in hostile environments that make image gathering difficult. The use of UAVs to take photographs may circumvent the hazards of hostile environments [29]. In such a case, developers may have to use existing reference images, blueprints, and technical drawings (if available) in lieu of gathering images [3].

The efficiency of the proposed procedural modeling-based, "low-complexity" workflow is yet to be fully evaluated. Therefore, future development of this idea should include user studies assessing VR training scenarios based on our workflow versus those based on photogrammetry, manual 3D modeling, or CAD models. These studies could be for VR production teams assessing the efficiency and level of customization among the different workflows, assessments of the digitized objects by VR users, or feedback from clients inspecting the results of the various digitization techniques. Using such experimental approaches, the barriers of utilizing VR-assisted personnel training cited in paragraph 1.1 may be more comprehensively addressed. Other future works may explore how the proposed workflow lends itself toward cultural heritage and preservation projects. Procedural modeling may be ideal for efficiently digitizing structures for heritage or historical preservation, given that CAD models generally do not exist for such structures. Scalability and stress tests, assessing digitization workflow effectiveness on larger and more complex objects, could reveal weaknesses of individual workflow steps and would also be suitable for future work.

5 Conclusion

A “low-complexity” workflow for digitizing complex real-world objects and environments for interactive virtual scenarios has been presented. This workflow combines image-based reference gathering and procedural modeling to simplify the digitization pipeline and give artists greater control over the 3D assets. The characteristics of the assets are controlled by the artist, not a scanned representation. The result (as demonstrated by our previous milking machine project) are highly customizable, VR-ready 3D assets that are easily updated to suit the needs of the virtual scenario. This approach avoids the ambiguity of “black box” techniques such as photogrammetry. It further reduces complexity by replacing 3D asset creation techniques with procedural modeling, which is more customizable and lends itself better to non-destructive iteration. While there exist implicit weaknesses to this methodology, further development and application will allow us to fully assess its potential.

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