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*Short Paper*

# End-to-end Color 3D Reproduction of Cultural Heritage Artifacts: Roseninsel Replicas

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**Abstract**

*Planning exhibitions of cultural artifacts is always challenging. Artifacts can be very sensitive to the environment and therefore their display can be risky. One way to circumvent this is to build replicas of these artifacts. Here, 3D digitization and reproduction, either physical via 3D printing or virtual, using computer graphics, can be the method of choice. For this use case we present a workflow, from photogrammetric acquisition in challenging environments to representation of the acquired 3D models in different ways, such as online visualization and color 3D printed replicas. This work can also be seen as a first step towards establishing a workflow for full color end-to-end reproduction of artifacts. Our workflow was applied on cultural artifacts found around the "Roseninsel" (Rose Island), an island in Lake Starnberg (Bavaria), in collaboration with the Bavarian State Archaeological Collection in Munich. We demonstrate the results of the end-to-end reproduction workflow leading to virtual replicas (online 3D visualization, virtual and augmented reality) and physical replicas (3D printed objects). In addition, we discuss potential optimizations and briefly present an improved state-of-the-art 3D digitization system for fully autonomous acquisition of geometry and colors of cultural heritage objects.*

**CCS Concepts**

• ***Computing methodologies*** → *Reconstruction; Rendering; 3D imaging;* • ***Human-centered computing*** → *Interaction paradigms;* • ***Hardware*** → *Scanners;*

## 1. Introduction

The demand for accurate 3D color representation of cultural heritage artifacts is steadily increasing. Especially virtual replicas (through online interactive visualization, virtual reality, augmented reality) and physical replicas (3D printed objects) are allowing immersive experiences for users and thus, institutions are increasingly deciding to exhibit them to preserve the originals in safe, controlled environments regarding climate, humidity, light and pollutants. The major contribution of this work is to highlight the most significant aspects of a 3D color reproduction workflow, which affects a user's perception of virtual and physical replicas. The replicas need to faithfully represent the originals and furthermore it is possible to deliver additional experiences not feasible with the original artifacts, such as physical interaction with objects, observing the details that aren't perceivable on the real objects, or seamless integration of additional 3D information.

### 1.1. Motivation

The Rose Island is a small island in the Starnberg lake in the state of Bavaria, where the royal villa, the "Casino", was built in 1853 on request of the king of Bavaria, Maximilian II. He was a passionate collector of antique findings, which he was showcasing in the dining room of the Casino [Web19d]. The association "Der Förderkreis Roseninsel Starnberger See e.V." aims to restore the "Roseninsel" island to its original state and to "redeem the royal casino artifacts from the darkness of the storage vaults by putting a number of them back on display at their original location". However, the Bavarian Palace Department does not support this objective due to numerous reasons - fire protection, possible damage caused by visitors and thus insurance-related questions would stand in the way. Therefore they took the decision to create 3D replicas of the originals and showcase them instead [Web19d]. The replication of five exhibits was funded by the "Bayerisches Staatsministerium der Finanzen und für Heimat", and the Fraunhofer Institute for Computer Graphics Research IGD reproduced them in cooperation with the Archaeological State Collection. Together with two other replicas, donated by the "Förderkreis Roseninsel" these seven objects are now shown in the Casino at Rose Island in a cabinet showcase made of maple wood [Web19b].

### 1.2. Challenges

Faithful representation of cultural heritage artifacts demands highest requirements from both the digitization and the reproduction method, regardless of the replicas being virtual (online 3D visu-





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**Figure 1:** *Selected artifacts from Roseninsel collection.*

alizations on websites, VR and AR, see section 4) or physical (3D print). The main requirement is the accurate representation of the pysical object (geometry and material) at a quality and fidelity that the reproduction is perceived by the viewer to be true to the original artifact. 3D digitization technologies are already breaking the resolution limit of the human eye, extracting geometrical details from physical surfaces at a granularity not even reachable by current 3D printers. Another crucial requirement is the accurate reproduction of colors. Each step in a color processing workflow, such as digitization and replication, potentially increases the color deviation of the reproduction from the original. In order to control the color deviation along the steps, all components possibly altering color perception need to be calibrated against a measured ground truth. In our workflow (overview in Figure 2), this is done by char-

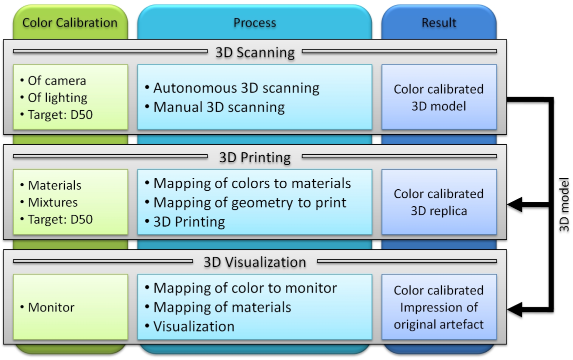


**Figure 2:** *Diagram of the end-to-end color 3D reproduction.*

acterizing the image sensor against a color target with known colorimetric response. Section 2 describes the approach used for the Roseninsel project. Going one step beyond colors, a physically realistic representation of optical material behavior of the object surface is even harder to achieve, but it yields the most realistic impression, especially when virtually interacting with a replica. The artifacts of the Roseninsel collection consist of matte, diffuse materials, thus accurate reproduction of the Roseninsel artifacts does not necessarily require capturing material behavior or modeling by physically based rendering (PBR) [RBS*18].

## 2. Digitization of the Artifacts

In November 2017 we digitized 27 findings from Roseninsel, which had to be handled with great care by conservators, thus the digitization was carried out at the workshop of the Bavarian State Archaeological Collection, where we set up two acquisition systems, based on photogrammetry. The first system is designed to acquire 3D data of cultural heritage objects up to a size of $40cm$. Images were captured with a Canon camera system (Canon 5DSr, EF 100mm Macro USM), which was mounted on a lightweight robot arm. Lighting environment was realized with two large softboxes behind the camera in order to ensure soft homogenous illumination of the objects. Objects were placed on a turntable, which was synchronized with the capturing system. The second system is appropriate for larger objects, up to a size of $1m$. A camera Nikon D610 was mounted on a tripod, and the other elements of the acquisition system were scaled accordingly; a larger turntable would hold objects up to $50kg$ and the homogenous lighting system would homogeneously illuminate objects up to $1m$. From 27 Roseninsel artifacts, 17 were digitized using the first system, the remaining 10 (larger and heavier objects) with the second system. The systems semi-automatically captured between 200 and 400 images, which were later used in image-based 3D reconstruction. The complete workflow for image-based (photogrammetric) 3D reconstruction consists of three main steps:

1. Calibration: Intrinsic camera calibration and color calibration through ICC profiles (characterization of the image sensor for a specific lighting environment)
2. Image acquisition under the same lighting environment as in calibration step: The camera positions for acquisition are predefined based on the shape and size of the object. The autonomous scanning system based on a robotic arm captures an image-set automatically, while for larger objects the position of the tripod has to be manually be adjusted.
3. Processing: Captured RAW images are converted to sRGB color space based on the ICC profile generated during calibration. Image masks are automatically generated based on the image background and sharpness of the image and applied to remove the image background content. The data from all previous steps is used in the image-based 3D reconstruction workflow, which involves Structure-from-Motion, Multi-View Stereo, Surface Reconstruction, and Texture mapping.

### 2.1. Results

The output of the digitization workflow are high-resolution 3D models with associated textures in sRGB color space. The geometry of the resulting models is represented by $4-10$ million polygons, textures were computed in $8192x8192$ pixels resolution. From 27 objects, 5 objects were selected for physical reproduction through color 3D printing. The process is described in section 3. The high-resolution 3D models were further processed with RapidCompact [Web19c] in order to get optimized 3D models for fast virtual reproduction without visual loss of quality. Figure 3 shows one of the resulting 3D models, visualized as a seamless transition from a wireframe model into a textured model.

## 3. Physical Reproduction

### 3.1. 3D Printing Workflow

A 3D printing workflow loads a textured 3D model and computes the material arrangements encoded as 2D image slices to control a multi-material 3D printer. We used a streaming-based pipeline consisting of the following components:

**Figure 3:** *"Lampe" artifact: photo (left), 3D model (right).*

1. Load RGB-textured 3D model (colors assumed to be stored as sRGB)
2. Arrange and rotate model in print tray to minimize print height and thus printing time
3. Voxelize model in print resolution and assign texture colors to surface voxels. texture sampling considers printer resolution and voxel anisotropy via mipmapping
4. Compute distance field to the model's surface voxels as in [BATU18]
5. Push color signal given on the surface voxels into full volume using distance field
6. Transform sRGB colors into CMYK tonals using an ICC color profile for each voxel
7. 3D halftoning of CMYK tonals to assign exactly one printing material to each voxel as in [BAU15]
8. Extract 2D image slices of print material arrangements readable by the 3D printer firmware interface

The pipeline was encoded in *Cuttlefish* (Version 2016) [IGD16] and used by the 3D printing service Alphacam [Web19a] that printed the models.

### 3.2. Full-Color 3D Printer

We used a Stratasys J750 multi-material polyjet 3D printer [Str16] to physically replicate the artifacts. This printer jets small droplets of resin (photopolymer) that are cured layer-by-layer with UV light. Multiple print heads allow mixing different resins with different optical or mechanical properties in high resolution creating composite materials. The resolution used in this work was $X \times Y \times Z = 600 \times 300 \times 940$ dpi. The printer was loaded with Vero Cyan (C), Vero Magenta (M), Vero Yellow (Y), Vero Black (K), Vero Pure White (W), Vero Clear and a support material. The latter is used to support overhanging structures during printing and is mechanically removed in a post process.

### 3.3. Printer Calibration and Characterization

To calibrate and characterize the printer we have printed targets and measured the color of each patch. In contrast to prints on paper such a measurement could not be made with spectrophotometers used in graphic arts because the aperture ratio (detection/illumination) used in such spectrophotometers results in biased measurements when highly translucent materials are measured [ABTU15]. Therefore, we used a custom setup employing a nearly colorimetric camera (Canon 5D) and a spectrally tunable light source [TU16]. Measurements were conducted using a bidirectional $0/45$ geometry with a CIED50 illuminant to conform to the connection space of ICC color management. Figure 4 shows the setup. Flat-fielding is performed to compensate the effect of spatially non-uniform irradiance. To convert RGB to CIEXYZ a second degree polynomial regression was used, whereas the transform matrix was estimated by capturing the ColorChecker SG with spectrally known 140 color patches. The printer was calibrated by printing ramps of the CMYK base materials, from pure white to the pure base material. The nominal mixing ratios were transferred in effective mixing ratios using the Murray and Davies model [Mur36] as described by Wyble and Berns [WB00] (linearization stage). To characterize the printer the cellular broad-band Neugebauer model [RB93] was used to predict CIEXYZ values from effective CMYK tonal values. The model employed 5 grid points and was fitted to color measurements of a total of $5^4 = 625$ patches uniformly covering the effective CMYK tonal space. An ICC profile was computed based on this model using a Gray-Component Replacement strategy minimizing black. For reproducing the scanned models, we used the relative colorimetric intent of this profile.

**Figure 4:** *Setup used for capturing color data: Color checker with known spectral data is captured to estimate the transform matrix.*

## 4. Virtual Reproduction

Physical reproduction is not the only way of reproducing artifacts. Results from 3D digitization (section 2) can serve multiple purposes in order to empower a broad audience to experience them in very realistic and immersive ways. We have prepared examples for three alternate forms of virtual reproduction.

### 4.1. Interactive Online Visualization (3D Viewer)

An up-to-date web browser is the only requirement for a broad online visualization - no special software and not even powerful hardware is needed - the 3D visualization even runs on a smartphone. The following link leads to an interactive online visualization of the Roseninsel results in 3D:
▷ https://www.cultlab3d.de/index.php/roseninsel
In collaboration with [Web19c], we developed a responsive, easy-to-use and freely configurable 3D object viewer, which can easily be realized with an online tool such as Turner3D [Web19e].

### 4.2. Virtual Reality (VR)

Virtual reality (VR) goes one step further by taking the user out of its normal environmental context. VR requires specific head-mounted displays to shield the viewer from the real environment and thus create the effect of immersion. To interact with the virtual

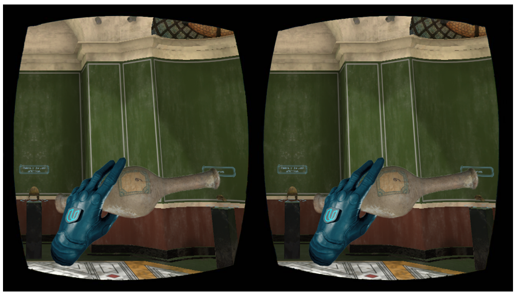

**Figure 5:** *Artifact presented in virtual reality.*

scene, the user holds specific controls in their hands, as in Figure 5 (the blue model of a hand). Using the controller, users can pick the artifacts up and turn them with a single hand and even move them close to their eyes to see details. The scene is rendered for each eye at a resolution of $1440 \times 1600$ pixels and a refresh rate of 90 Hz with a horizontal field of view of $110^{\circ}$. For a fast, responsive VR experience, the 3D models have to be optimized while maintaining the optimal balance between quality and size. Using RapidCompact [Web19c] we optimized the 3D models to $20,000$ polygons and $4k$ textures ($4096 \times 4096$ pixels).

### 4.3. Augmented Reality (AR)

Augmented reality essentially presents the user with the real environment, seamlessly adding virtual content to it. We are using an Apple 12,9" iPad Pro, which comes with the software "ARKit" integrated in the iOS operating system, allowing for straightforward AR experience. The high-quality data from 3D scanning was optimized using RapidCompact [Web19c] and prepared in Apple's open USDZ file format for use with AR. By visiting the following link using the iPad native browser (Safari), the AR scene runs without installing additional software:
▷ https://www.cultlab3d.de/index.php/roseninsel-ar/

## 5. Optimizations and Future Work

To achieve (scientifically) accurate end-to-end color reproduction, some crucial optimizations have to be made, especially in the digitization workflow. Since the implementation of our fully automated mass digitization pipeline CultLab3D [SRT*14] we have continuously improved our robotic scanning systems by addressing new requirements and challenges, such as color accuracy, shiny surface materials and geometry complexity (surface occlusions and cavities). CultLab3D consists of different, smaller and mobile scanning modules, that can also be operated independently. For this project we adapted an early prototype version of the mobile CultArm3D desktop module that combined a light-weight collaborative robot arm with a small desktop turntable to place objects on. Images were acquired by a DSLR camera mounted on the end effector of the robot arm. To avoid dynamic highlights, specularities and shadows on the object surface, a large soft box setup was used around the turntable to homogeneously illuminate the object from all sides. The setup was appropriate for the presented objects. However, for larger objects and objects with shiny surfaces we faced two challenges. First, the required robot workspace spatially scales up with the object size and cannot be provided by the recent collaborative and smaller robot arms. Secondly, to capture shiny surface without specularities, a more sophisticated light setup must be deployed. In the photography domain, the polarization of light is successfully applied to reduce specularities with respect to the angle of incidence of the light and the camera. In the current version (Figure 6)

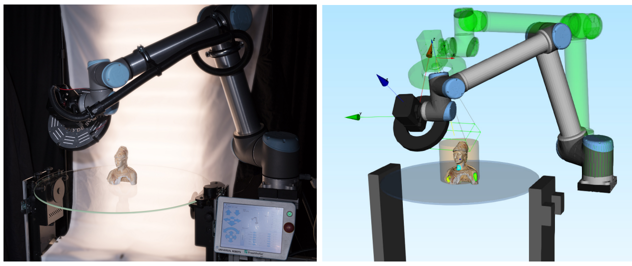

**Figure 6:** *CultArm3D-P: Real and virtual scanning environment.*

of our scanning system we addressed the mentioned issues by deploying a robot arm with a larger workspace and sufficient payload capabilities to not only carry the camera but also a mounted ring light. This allows usage of polarization filters to remove specularities without losing detail in focused areas. The acquisition system automatically adjusts the distance of the camera to the object's surface based on an initial quick scan that provides a fast but sufficient 3D surface reconstruction. Since the ring light moves together with the camera this also ensures an equal light intensity on focused surfaces that are later used for reconstruction and texturing. Besides the focus distance adaptation, camera views are also planned and positioned with respect to the local surface quality of the scan, while resolving occlusions caused by complex surface geometry.

**Figure 7:** *Left image (from left to right): Original object, 3D printed replica, and 3D rendered virtual model. Right image: Photo of real scene and AR view on iPad.*

## 6. Conclusions

We address a complete workflow for end-to-end color reproduction of cultural heritage artifacts. Our case study was a collection of artifacts from Roseninsel, where the physical replicas are on public display, while the originals are safely stored. Additionally, three types of virtual replicas were created from digitized artifacts: 3D visualization in a web browser, Virtual Reality, and Augmented Reality experiences. Regarding human perception, we achieved a very realistic appearance of the replicas, because the matte materials and simple geometry of the objects were suitable for straightforward photogrammetric acquisition. However, this approach is not sufficient for shiny materials and complex surfaces. Based on the findings of this study, we further improved and extended our current acquisition system to a point where it now is able to autonomously digitize even difficult objects considered too challenging for conventional photogrammetric acquisition systems. The Roseninsel collection posed interesting challenges for color-accurate reproduction, even though the materials found on the surfaces were diffuse. Artifacts partially or entirely consisting of reflective or even translucent materials, bring upon the next challenge for digitization. Physically realistic reproduction requires measuring the material response systematically for combinations of a set of different incoming light and outgoing observer angles. We are already working on the improvement of our measurement systems to satisfy this requirement as well.

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