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Non-Contact 3D Acquisition of Challenging Museum Objects for Cultural Heritage Digitalization

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ABSTRACT

The digitalization of cultural heritage represents an important field in contemporary museum object preservation, enabling documentation, research, virtual presentation, and long-term archiving without direct intervention in original artifacts. The aim of this study was to investigate the suitability of various non-contact technologies for acquiring geometric and visual information from museum objects and to create accurate digital twins of these artifacts.The research was conducted in collaboration with the National Museum of Slovenia and focused on selected examples of silver-plated tableware manufactured around 1900. The acquisition of these objects posed significant challenges due to the high reflectivity of metallic surfaces, complex geometries, and the presence of fine reliefs and decorative details. Within the experimental framework, several acquisition technologies were compared, including laser triangulation, structured light scanning, and photogrammetry. Initial test acquisitions were performed using the EinScan HX system, which supports both laser triangulation and structured light scanning. Simultaneously, photogrammetric acquisition was carried out using flash photography and diffuse illumination. Subsequently, a David 3D structured-light system was employed to capture both geometric and color information from the selected objects. Based on the preliminary results, the research focused on optimizing the photogrammetric workflow through the introduction of polarization filters to reduce unwanted reflections. Further improvements included the use of two polarized light sources and the development of a semi-automated background removal procedure, which significantly enhanced the quality of geometric reconstruction. As an additional improvement, the use of the X-Rite ColorChecker Passport color reference target was proposed to ensure greater color accuracy of the captured models. The results demonstrate that appropriately optimized photogrammetry combined with polarized illumination can provide an effective solution for the acquisition of challenging museum objects. The study contributes to the development of cultural heritage digitalization methodologies and provides a foundation for the creation of high-quality digital twins of museum artifacts.

KEY WORDS
Silver plated museum objects, digital twin, photogrammetry, 3D acquisition, structured-light scanning, laser triangulation

1. Introduction

The rapid development of digital technologies has significantly transformed the documentation, preservation, and presentation of cultural heritage. Three-dimensional (3D) digitization has become an indispensable tool for museums, archives, and conservation institutions, enabling accurate documentation, virtual presenta-

tion, scientific analysis, restoration planning, and long-term preservation of valuable artefacts (Mateus et al., 2019; Adamopoulos, Rinaudo & Ardissono, 2021).

Among the various applications of digital heritage, the creation of digital twins has gained increasing importance because it enables the preservation of both geometric and visual information while reducing the need for physical handling of fragile museum collections (Adamopoulos, Rinaudo & Ardissono, 2021).

Despite the rapid development of optical acquisition systems, selecting an appropriate digitization technology remains a challenging task. The quality of 3D acquisition depends not only on the accuracy of the measuring system but also on the optical properties of the object, including surface reflectivity, transparency, texture, colour, geometry and accessibility (Mathys et al., 2015; Iakovaki et al., 2026).

Highly reflective metallic objects belong to the most demanding categories for optical digitization. Specular reflections frequently cause missing data, reconstruction artefacts, geometric inaccuracies and colour distortions regardless of whether laser scanning, structured-light scanning or photogrammetry is employed (Angheluţă & Rădvan, 2020; Melendreras Ruiz, Marín Torres & Sánchez Allegue, 2021).

Several non-contact acquisition technologies are currently used for cultural heritage digitization. Laser triangulation provides high geometric accuracy but is sensitive to reflective materials (Hermary, n.d.). Structured-light scanning generates dense and accurate point clouds; however, its performance decreases when scanning highly reflective surfaces (Eiríksson et al., 2016). Photogrammetry has become one of the most widely adopted techniques because it provides high-quality texture information, requires relatively inexpensive equipment and allows flexible acquisition workflows, although its success strongly depends on controlled illumination conditions and image quality (Guidi, Gonizzi & Micoli, 2014; Iakovaki et al., 2026).

Recent studies indicate that no single acquisition technology is universally suitable for all museum objects. Instead, successful digitization relies on optimized acquisition workflows that combine appropriate hardware, illumination, image preprocessing and reconstruction procedures according to the optical properties of the artefacts (Mathys et al., 2015; Adamopoulos, Rinaudo & Ardissono, 2021).

The present research was conducted in collaboration with the National Museum of Slovenia and focused on silver-plated historical tableware manufactured around 1900. These artefacts represent a particularly demanding case due to their heterogeneous optical properties, ranging from reflective, highly polished areas to partially tarnished and less reflective regions. The acquisition was further complicated by their complex geometry and intricate ornamental details.

Unlike many previous comparative studies, the objective of this research was not only to evaluate three non-contact acquisition technologies (laser triangulation, structured-light scanning and photogrammetry) but also to develop an optimized workflow for digitizing highly reflective museum objects. Particular attention was devoted to minimizing reflections using cross-polarized illumination, improving image preprocessing and optimizing the photogrammetric reconstruction process. The proposed methodology aims to provide practical guidelines for producing accurate digital twins suitable for museum documentation, conservation and future digital presentation.

2. Materials and Methods

2.1. Museum objects

The experimental work was carried out in cooperation with the National Museum of Slovenia. The investigated artefacts consisted of selected silver-plated tableware manufactured around 1900, including a jug and a wine goblet (Figure 1).
These objects were selected because they represent typical silver museum artefacts that combine highly polished, reflective surfaces with partially tarnished or darkened areas, thereby significantly complicating optical 3D acquisition.



» **Figure 1:** *Selected museum objects used in the experimental investigation*

The combination of smooth polished surfaces, curved geometry and fine ornamental details makes such objects particularly demanding for non-contact digitization. These characteristics frequently produce specular reflections, incomplete surface reconstruction and colour inaccuracies when conventional optical acquisition methods are applied.

2.2. Experimental equipment

Three non-contact 3D acquisition technologies were investigated and comparatively evaluated:

- Laser triangulation using the EinScan HX portable hybrid scanner (Shining 3D);
- Structured-light scanning using both the structured-light mode of the EinScan HX and the David 3D structured-light scanning system;
- Image-based photogrammetry using a professional DSLR camera with studio lighting.

The photogrammetric system consisted of a digital camera mounted on a tripod, interchangeable lenses, studio flash units equipped with softboxes, a motorized turntable, linear polarizing filters mounted on the light sources, a circular polarizing filter mounted on the camera lens, and a colour calibration target (X-Rite ColorChecker Passport). Image processing and 3D reconstruction were performed using Agisoft Metashape together with Adobe Photoshop for image preprocessing.

2.3. Experimental workflow

The experimental investigation was designed as a comparative study in which three different acquisition technologies were evaluated under controlled laboratory conditions.

The first phase focused on the comparison of laser triangulation, structured-light scanning and conventional photogrammetry in order to identify the principal limitations of each technique when applied to reflective museum objects.

Laser triangulation was performed after calibration of the EinScan HX system. The scanner operated in Laser Scan mode with a point spacing of 0.2 mm. Since reflective museum artefacts could not be marked directly, positioning targets were attached to externally manufactured 3D-printed dodecahedrons placed around the object. After scanning one side, the object was carefully repositioned to capture all visible surfaces while maintaining the reference targets.

The structured-light mode of the EinScan HX was subsequently evaluated using an identical acquisition procedure. Due to strong reflections from the metallic surfaces, the acquired geometry proved insufficient for reliable reconstruction, and the investigation continued using the David 3D structured-light system, which was specifically designed for high-resolution structured-light acquisition.

In parallel, an initial photogrammetric acquisition was performed using diffuse illumination and studio flash photography. Images were captured from multiple viewing angles while ensuring sufficient overlap between consecutive photographs to support reliable feature matching and camera alignment during reconstruction.

2.4. Workflow optimization

Based on the results obtained during the preliminary acquisitions, the research focused on optimizing the photogrammetric workflow (Figure 2).

The principal improvement consisted of introducing cross-polarized illumination. Linear polarizing filters were mounted on the studio light sources, while a circular polarizing filter was attached to the camera lens. The orientation of the filters was adjusted to minimize specular reflections originating from the metallic surfaces.



» **Figure 2:** *Experimental photogrammetric setup with polarizing filters; the museum object is indicated in red*

In the final acquisition stage, two polarized light sources were employed simultaneously, providing more homogeneous illumination and further reducing residual reflections on the object surface. Multiple object orientations were recorded to ensure complete coverage of complex geometrical features.

2.5. Image preprocessing and 3D reconstruction

Captured photographs were processed prior to photogrammetric reconstruction.
White balance and colour consistency were adjusted using reference images.
A semi-automated background removal procedure was developed in Adobe Photoshop by recording and applying automated processing actions to the complete image dataset. This approach significantly reduced manual intervention while improving segmentation consistency between photographs.

The processed image sets were imported into Agisoft Metashape, where the standard photogrammetric workflow was applied, including image alignment, sparse point cloud generation, dense point cloud reconstruction, polygon mesh generation and texture mapping.

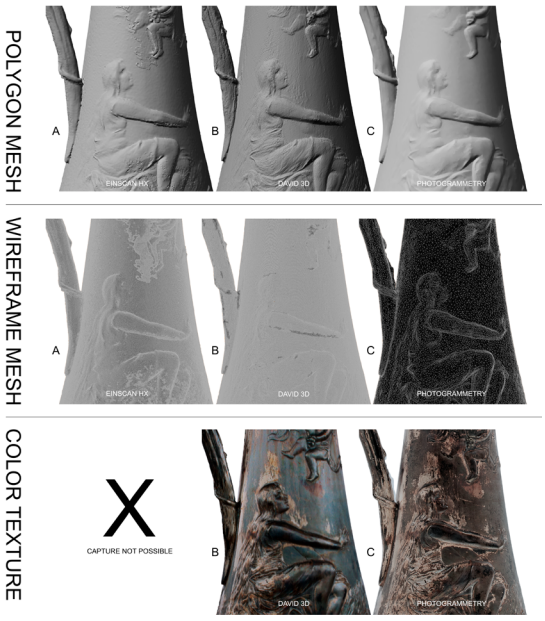
The reconstructed models obtained from all investigated acquisition technologies were subsequently compared with respect to geometric completeness, reconstruction quality, preservation of fine surface details and colour fidelity.

3. Results

3.1. Comparison of the investigated acquisition technologies

The three investigated non-contact acquisition technologies exhibited different performance when applied to highly reflective museum objects. The results demonstrated that the optical properties of silver-plated surfaces significantly influenced the quality of geometric reconstruction and texture acquisition.

Laser triangulation enabled reliable acquisition of larger surface regions and acceptable geometric accuracy for moderately reflective areas.



» **Figure 3:** *Comparison of representative reconstruction results obtained using laser triangulation (A), structured-light scanning (B), and optimized photogrammetry with cross-polarized illumination (C)*

However, highly polished surfaces generated strong reflections that reduced the completeness of the reconstructed geometry. In addition, the absence of colour acquisition limited the suitability of this approach for producing realistic digital twins intended for museum presentation.

The structured-light systems produced dense point clouds with satisfactory geometric detail under favourable conditions. Nevertheless, both investigated systems were sensitive to strong specular reflections originating from the metallic surfaces. Missing surface regions and reconstruction artefacts were observed primarily on highly polished curved areas, requiring extensive post-processing before a complete model could be obtained.

Initial photogrammetric acquisition performed under conventional studio illumination produced high-quality colour information but suffered from numerous reflections visible on the captured images. These reflections negatively affected feature detection during image alignment and reduced the completeness of the reconstructed geometry. Results are summarized in Figure 3.

3.2. Optimization of the photogrammetric workflow

Following the preliminary experiments, the photogrammetric acquisition workflow was progressively optimized to minimize unwanted reflections.

The introduction of cross-polarized illumination significantly reduced specular reflections on the object surface, resulting in improved image quality and more reliable feature detection during photogrammetric processing. The use of two polarized light sources provided more homogeneous illumination and reduced residual reflections in shadowed regions (Figure 4).



» **Figure 4:** *Reduction of specular reflections using a polarizing filter: (left) before adjustment; (right) after adjustment*

An additional improvement was achieved through semi-automated background removal prior to reconstruction. Eliminating unnecessary background information reduced the amount of irrelevant image data processed by the reconstruction software, accelerated model generation and improved segmentation consistency across the complete image dataset.

3.3. Quality of the reconstructed digital twins

The optimized photogrammetric workflow produced the most complete digital twins among the investigated approaches. Fine decorative elements, engraved details and complex free-form surfaces were recon-

structed with high geometric continuity while simultaneously preserving realistic colour information.

Depending on the complexity of the individual artefacts, between 150 and 300 photographs were acquired for each object. The number of photographs and object orientations was adjusted according to the surface geometry, roughness and the presence of movable components. The optimized workflow enabled successful reconstruction of complete digital twins while maintaining efficient computational performance during processing.

The proposed acquisition methodology proved particularly effective for reflective museum artefacts, demonstrating that careful preparation of the acquisition environment is equally important as the selection of the acquisition technology itself. The combination of polarized illumination, optimized image acquisition and semi-automated image preprocessing considerably improved both geometric reconstruction and texture quality (Figure 5).



» **Figure 5:** *Final digital twin of the museum object reconstructed using the optimized photogrammetric workflow with cross-polarized illumination*

4. Discussion

The performed experiments demonstrated that the successful digitization of highly reflective museum objects depends not only on the selected acquisition technology but also on the optimization of the entire acquisition workflow. The comparison of laser triangulation, structured-light scanning and photogrammetry revealed that each technology exhibits specific advantages and limitations when applied to reflective metallic artefacts.

Laser triangulation provided reliable geometric measurements for less reflective surfaces; however, its performance decreased on highly polished regions due to strong specular reflections. Similarly, structured-light scanning produced dense geometric data but proved sensitive to reflective surfaces, resulting in incomplete reconstruction of certain object regions.

Among the investigated approaches, the optimized photogrammetric workflow produced the most complete and visually realistic digital twins for the investigated museum objects. The introduction of cross-polarized illumination substantially reduced specular reflections, improving image quality and increasing the reliability of feature detection during photogrammetric reconstruction. In addition, the semi-automated image preprocessing workflow contributed to more consistent image segmentation and reduced manual processing time.

The results indicate that, for highly reflective museum objects, careful control of illumination conditions is equally important as the selection of the acquisition technology itself. Rather than relying solely on advanced scanning equipment, the proposed workflow demonstrates that a properly optimized photogrammetric approach can produce highly accurate and visually realistic digital twins while requiring relatively accessible hardware.

The developed methodology therefore provides practical recommendations for museums and cultural heritage institutions seeking cost-effective solutions for the digitization of challenging historical artefacts. Furthermore, the proposed workflow can be adapted for other reflective objects with similar optical properties, extending its potential application beyond the investigated case study.

5. Conclusions

This study investigated the applicability of three non-contact acquisition technologies for the digitization of highly

Table 1

Comparison of the investigated non-contact acquisition technologies

Technology	Geometry	Colour	Performance of reflective surfaces	Completeness	Overall suitability for museum digitalization
Laser triangulation	High	No	Moderate	Medium	Medium
Structured light	High	Limited	Low	Medium	Medium
Optimized photogrammetry	High	Excellent	High	High	Excellent

reflective museum objects. Laser triangulation, structured-light scanning and photogrammetry were experimentally evaluated using selected silver-plated historical artefacts from the National Museum of Slovenia.

The comparison demonstrated that all investigated technologies are capable of acquiring three-dimensional data; however, their performance varies considerably when applied to reflective metallic surfaces. While laser triangulation and structured-light scanning encountered limitations caused by specular reflections, the optimized photogrammetric workflow produced the most complete and visually realistic digital twins.

The introduction of cross-polarized illumination, optimized photographic acquisition and semi-automated image preprocessing significantly improved reconstruction quality by reducing reflections and increasing the completeness of the reconstructed geometry. The proposed methodology proved to be an effective and practical and accessible solution for the digitization of challenging museum objects.

The presented workflow contributes to the development of practical methodologies for cultural heritage digitization and provides useful guidelines for museums involved in the creation of accurate digital twins for documentation, conservation and digital presentation.

Future research will focus on further improving colour accuracy through colour-managed acquisition workflows, quantitative accuracy assessment of reconstructed models, and the integration of complementary acquisition technologies for even more demanding museum artefacts.

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