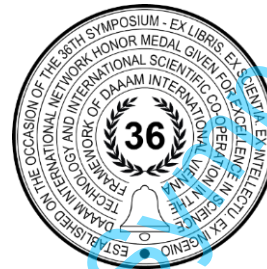


Reverse Engineering for Cultural Heritage Digitization and Tactile Museum Replicas

Dana Kubátová, Kateřina Skovajsa, Václav Blábol



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Abstract

Cultural heritage digitization supports long-term preservation, research and public access. This paper examines how reverse engineering can connect the documentation of museum objects with digital presentation and the production of tactile replicas. It reviews photogrammetry, light detection and ranging, reflectance transformation imaging, computed tomography and surface scanning, distinguishing geometric acquisition from surface-detail analysis. A workflow is proposed comprising data acquisition, processing, three-dimensional model creation and verification, followed by digital presentation or replica production. Examples from the author's museum-related presentation show relief objects and their physical copies, together with two digital coin models acquired using different systems and point spacings. These examples provide qualitative documentation rather than a quantitative accuracy assessment. The paper also discusses proposed geometric adaptations for tactile use, manufacturing considerations, accessibility and ethical issues. Its main conclusion is that digital documentation can support tactile interpretation, but geometric fidelity, replica durability and usability require separate validation. Future work should combine measured geometric deviations with manufacturing data and evaluation by visitors with visual impairments.

Keywords: reverse engineering; cultural heritage digitization; 3D scanning; tactile replicas; museum accessibility

1. Introduction

Digitization is becoming an important part of cultural heritage conservation. It preserves information about physical objects and can make heritage accessible to people who cannot reach the original exhibits for geographical, physical or other reasons. Three-dimensional digitization of cultural heritage has a substantial research background [1].

Digital technologies enable digital archives and virtual museums while supporting new forms of education and presentation. Historical documents, books, maps, photographs, films, works of art and three-dimensional collection objects can all be digitized. However, the use of 3D data also raises questions of workflow consistency, interoperability and quality assessment, as discussed by Storeide et al. [3].

Reverse engineering provides a technical approach to the digitization of physical objects. In engineering practice, it is used to obtain knowledge of an existing product, analyse, improve or modernize it, or develop a new product based on the original solution. This principle can also be applied to cultural heritage. Fig. 1 illustrates non-contact acquisition of a sculpture and the display of its digital representation. The aim of this paper is to describe the path from museum-object documentation to tactile replicas and identify the validation needed at each stage.



Fig. 1. Illustrative non-contact 3D digitization of a sculpture and display of its digital model. [6].

2. Reverse engineering in cultural heritage

Reverse engineering can be characterized as a process in which an existing physical object is analysed to obtain information about its geometry, structure, construction or method of manufacture.

In cultural heritage, the same principle can be used to create a digital representation of a historical object or work of art. Museum applications include documentation of historical objects and buildings, digitization of artworks, processing of archaeological finds, and creation of digital archives, virtual exhibitions and tactile models.

An important application is the conversion of a physical artefact into a digital 3D representation. The resulting model can subsequently support research, teaching or presentation in a virtual museum. Hess et al. [2] discuss workflows and quality control for museum-object imaging, providing a methodological context for this process.

3. Digitization methods

The choice of digitization method depends on the object's characteristics, dimensions and surface, the required accuracy and the acquisition conditions. The following overview covers photogrammetry, light detection and ranging (LiDAR), reflectance transformation imaging (RTI), computed tomography (CT) and 3D scanning. RTI is included as a complementary method for examining surface appearance and detail.

3.1. Photogrammetry

Photogrammetry derives spatial information about an object from photographs. In cultural heritage, it can be used to document collection objects, buildings and archaeological sites.

3.2. Light detection and ranging

LiDAR uses laser-based measurements to acquire spatial data about objects and their surroundings. In cultural heritage, it can be particularly useful for larger subjects such as historical buildings, complexes and archaeological sites. Masic et al. [7] presented a low-cost drone platform equipped with a LiDAR sensor for terrain mapping and tested it at two field locations. Their study provides an example of spatial data acquisition over a larger environment.

3.3. Reflectance transformation imaging

RTI enables the examination of an object's surface under varying illumination conditions. It can be useful where surface texture, relief or small surface details are important. Its role in this workflow is surface-detail analysis rather than direct acquisition of a complete geometric model.

3.4. Computed tomography

CT can also provide information about an object's internal structure. In contrast to methods primarily concerned with the surface, it can reveal internal features of the object under examination.

3.5. Three-dimensional scanning

3D scanning provides a spatial representation of an object's surface. Depending on the object and equipment, handheld or machine-based scanning systems can be used. Fig. 2 shows practical acquisition of a relief collection object on measuring equipment.

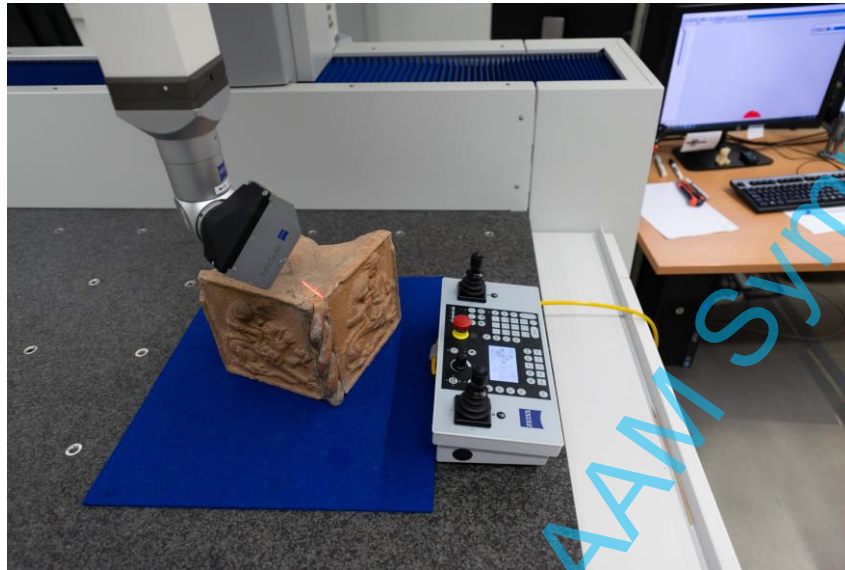


Fig. 2. Surface acquisition of a relief collection object on measuring equipment. [6].

4. Proposed digitization workflow

The proposed workflow comprises data acquisition and processing, creation of a 3D model and verification. Subsequent use branches into digital presentation and production of a physical replica (Fig. 3).

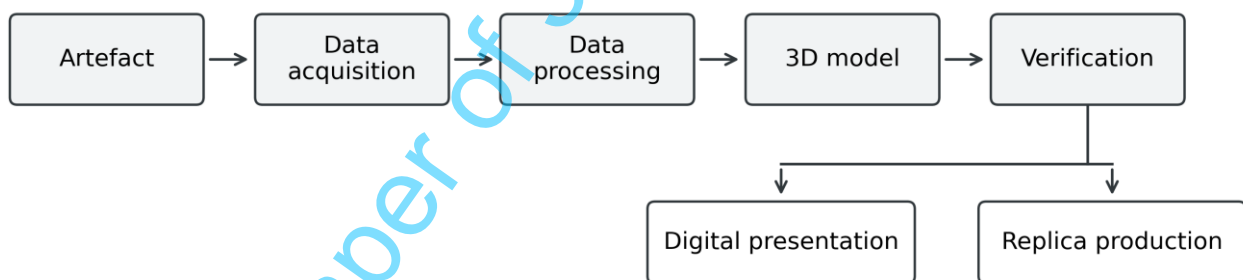


Fig. 3. Museum-object digitization workflow and subsequent uses of the resulting 3D model. [6].

The first step is to select a suitable digitization method, followed by data collection and processing. The resulting digital model can serve as documentation or as the basis for further modifications and physical-model production. Verification should also assess geometric changes introduced when measured data are converted into the final model. Kubatova and Kaufnerova [8] described a comparison between a polygon mesh and a solid model generated from scanned data. This approach provides a methodological basis for checking the conversion; their experimental results cannot be transferred directly to the museum exhibits discussed here.

5. Application in museum practice

An example of reverse engineering is the digitization of selected collection objects from the Manský dům at Krivoklát, documented in the author's presentation [6]. Fig. 4 compares the appearance of relief objects and their copies. The example links documentation of the original to production of a physical replica, but does not itself provide a quantitative assessment of geometric agreement.



Fig. 4. Two examples of relief collection objects and their copies. In each pair, the coloured object is on the left and its grey copy on the right. [6].

Digital data can support analysis, documentation, education and presentation. A physical replica can also make selected shape and spatial information accessible to visitors for whom visual presentation alone is insufficient.

The supporting material also includes a visual comparison of digital coin models (Fig. 5). The presentation specifies a point spacing of 0.2 mm for HandySCAN 700 and 0.05 mm for ZEISS LineScan; both examples are described as polygon meshes. These are parameters reported for the individual examples, rather than measured accuracy values. The visual comparison can support discussion of relief capture, but the effect of point spacing cannot be isolated from the effects of the equipment and data processing.



Fig. 5. Digital coin models: left, HandySCAN 700, point spacing 0.2 mm; right, ZEISS LineScan, point spacing 0.05 mm. [6].

6. From the digital model to a tactile replica

An important benefit of connecting reverse engineering with museum practice is the potential to produce tactile models. These enable the shape, relief and other spatial properties of an object to be explored through touch.

This form of presentation may be particularly useful for visitors with visual impairments. The digital 3D model can form an intermediate stage between the original exhibit and a physical tactile replica. Rossetti et al. [4] investigated an interactive cultural-site model combining tactile and audio information. Kantaros et al. [5] examined digitization and the production of museum replicas intended for visitors with disabilities. These studies provide relevant contexts for accessible interpretation.

Replica production using fused filament fabrication (FFF) requires consideration of material properties and print settings. Pandzic et al. [9] review the effects of material, part orientation, layer height and infill structure on the mechanical properties of printed parts. For tactile replicas, this implies a need to assess durability under repeated handling.

The process can be described in eight steps: (1) select a suitable exhibit; (2) digitize it; (3) create a digital 3D model; (4) verify and, if necessary, modify the geometry; (5) prepare the model for manufacturing; (6) produce a physical replica; (7) add a description and other information elements; and (8) incorporate the model into the museum exhibition.

Fig. 6 illustrates a possible geometric adaptation before tactile-model production. Thickening the handle and reinforcing its connections are proposed changes only; they are not documented modifications of the collection objects presented in the museum application.

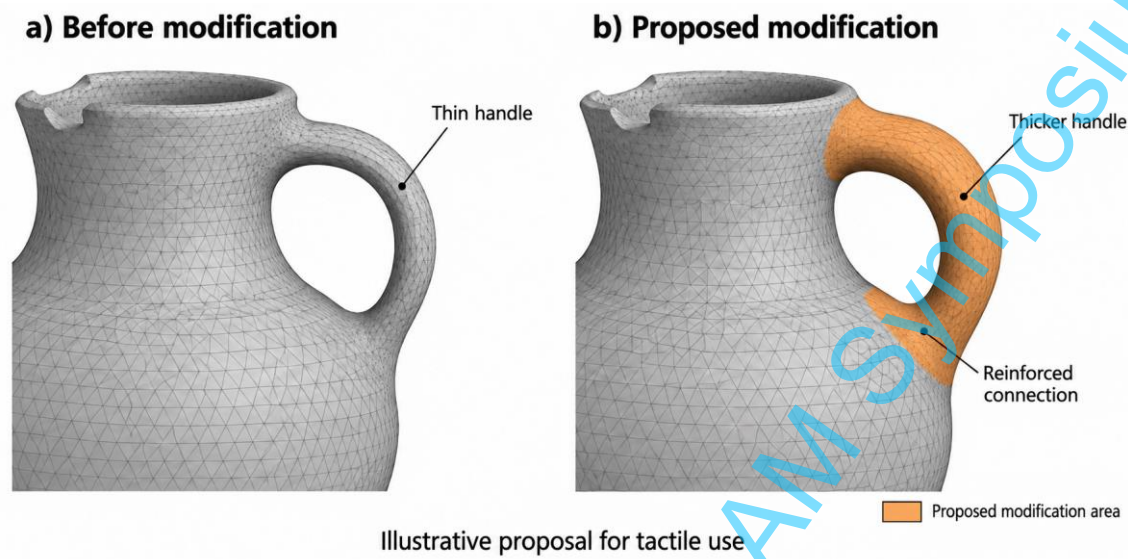


Fig. 6. Illustrative proposal to thicken a handle and reinforce its connections for tactile use. Orange indicates the proposed modification area. [6].

7. Digitization and heritage accessibility

Digitization is more than the technical conversion of a physical object into a digital representation. In cultural institutions, it can also change how visitors engage with heritage. Fig. 7 illustrates intended tactile exploration of a physical replica.



Fig. 7. Illustrative tactile exploration of a replica at a museum station. [6].

A digital model can preserve spatial information about an exhibit, support a digital archive, provide access through a virtual environment, enable teaching materials, facilitate research, and serve as the basis for physical replicas and tactile models.

Bevrnja et al. [10] describe additive manufacturing as a means of improving information access for people with visual impairments. Their public-transport proposal combines a 3D-printed aid with a tactile map, a QR code and the possibility of audio information. Although developed in a different setting, it may inform the integration of tactile and audio information at a museum station. The study does not validate the museum replicas discussed here.

8. Technical and ethical considerations

Cultural heritage digitization requires consideration of technical capabilities as well as legal and ethical issues. A digital copy of a historical object or artwork can be a valuable information resource, but its creation and use may raise questions of ownership, copyright and heritage protection.

The purpose of creating the digital model and its intended subsequent use should be assessed before digitization begins. Where possible, the model should be accompanied by information about data provenance, the acquisition method and the purpose for which it was created. Any geometric adaptation for tactile use should be identified so that an interpretive replica is distinguishable from documentation of the original.

9. Discussion

The connection between reverse engineering and cultural heritage digitization is interdisciplinary, bringing together engineering, information technology, museum practice and heritage conservation.

The digitization methods provide different types of information. Photogrammetry can capture an object's spatial appearance, LiDAR can acquire data over larger environments, RTI supports the examination of surface detail, CT reveals internal structure, and 3D scanning captures surface geometry. The choice must nevertheless be based on the object's properties and the intended result.

The available material contains images of original objects, digital models and physical copies, together with selected acquisition and processing parameters. Point spacings of 0.05–0.2 mm are reported for the coin models; these values do not constitute experimental verification of accuracy. Measured geometric deviations, manufacturing times, quantitative model comparisons and user evaluations of tactile replicas are not currently available. For subsequent case studies, quantitative assessment should include registration of the acquired surface meshes and scans of manufactured replicas in a common coordinate system, followed by point-to-surface distance analysis. Mean absolute surface deviation, root-mean-square deviation and maximum absolute deviation, together with colour-coded surface deviation maps, are proposed to identify both overall discrepancies and local loss of relief detail. The measurement protocol should document registration strategy, spatial sampling, uncertainty and repeatability, and specify relevant standards only after their applicability to the selected acquisition and inspection tasks has been established. These are proposed evaluation metrics, not results of the present study. Thus, the current contribution documents an application and proposes a workflow rather than demonstrating measured accuracy.

10. Further research

Further research should compare digitization methods on selected museum objects using a documented reference measurement and repeatable evaluation protocol. Planned measures include mean absolute, root-mean-square and maximum surface deviations, spatial deviation maps of scans and manufactured replicas, data volume, acquisition and processing time, production time and material consumption. The effects of surface characteristics, sampling and alignment procedures should be examined separately wherever practical. Such measurements will allow geometric fidelity to be assessed independently of the requirements for tactile interpretation.

Proposed tactile adaptations, including handle thickening and reinforcement of vulnerable connections (Fig. 6), should undergo structured usability testing with participants with visual impairments. The evaluation should examine tactile readability of relief and shape, ease of handling, comfort, orientation, safety and user preference. Feedback should be compared with geometric differences between the original digital documentation and the adapted replica to balance ergonomic accessibility against historical fidelity. Durability under repeated handling should also be evaluated. No such user testing or quantitative validation is claimed for the examples reported in this paper.

11. Conclusion

Reverse engineering can support cultural heritage work as well as industrial applications. Combined with 3D digitization methods, it enables physical exhibits to be converted into digital representations for documentation, research, education, virtual presentation and replica production.

For museum practice, the key opportunity is to create a digital model that can be adapted to a defined purpose. Tactile models offer a promising way to broaden heritage interpretation and improve access for visitors with visual impairments. However, a useful tactile adaptation and faithful documentation of the original have different requirements, and any intentional modifications should remain explicit.

Further development should be based on practical case studies that quantify digitization performance and test suitability for different cultural artefacts. The examples presented here motivate that work but do not establish measured accuracy or validated tactile usability.

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