Form, Data, Matter: Photogrammetry and Digital Fabrication at the Service of Safeguarding the Built Cultural Heritage

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Abstract. Documentation of built cultural heritage is an important safeguarding strategy. However, the use of traditional documentation techniques, based on the direct acquisition of measurements with analog devices, makes the process time-consuming, inaccurate, and often inadequate for recording complex shapes, often found in the ornaments of certain architectural styles. This work explores the use of photogrammetry combined with digital fabrication in order to develop a methodology to document these elements of high geometric complexity, creating a workflow that connects digital techniques to traditional materialization techniques, exploring the potential of documentation to translate back into matter similar to that of the documented object. Seeking to validate these workflows, a series of prototypes are made in different materialities to evaluate the different techniques employed.

Keywords: Digital Heritage, Digital Fabrication, Built Cultural Heritage, Restoration, Photogrammetry

1 Introduction

When we talk about built cultural heritage, documentation emerges as an important safeguarding strategy, as it allows the reproduction of the information contained in the form and matter of buildings at other points in time and space. However, the use of traditional techniques, based on the direct acquisition of key measurements with analog tools to produce 2D drawings, makes the documentation process time-consuming, imprecise, and often inadequate for recording complex forms. Moreover, ambiguities and inconsistencies in representations are common, since drawings are, as a rule, produced individually in conventional CAD tools (GROETELAARS, 2015). On the other hand, the growing scarcity in the availability of craftsmen specialized in interpreting and producing artifacts from these representations raises suspicions about the suitability of this type of record to allow future reconstitutions of damaged parts, an action common to restoration processes (NOGUEIRA et al., 2019). This is a crucial point, since the goal of the restoration process is to preserve and reveal the aesthetic and historical value of the monument and should be based on the original materiality and authentic documents. It must cease in the moment the conjecture begins (ICOMOS, 1964). In this context, Digital Information and Communication Technologies (DICTs), such as photogrammetry and digital fabrication, present the possibility of improving the way the documentation of cultural heritage is carried out, allowing the creation of methodologies based on non-intrusive techniques that do not damage the object to be documented (ICOMOS, 1996).

With these considerations in mind, technologies for digital capture and reconstruction of objects, such as photogrammetry and 3D scanning, have proven to be an effective tool for heritage documentation, providing another approach to the morphology of the object of study, allowing its storage, manipulation and fabrication, opening a series of possibilities for production methodologies and use of this type of record. This work focuses on the use of digital reconstructions using Dense Stereo Matching (DSM) photogrammetry as a capture method, selected for being the most accessible, having as a minimum requirement only the possession of a camera and a computer equipped with some softwares.

The objective of this work is the development of a methodology to operationalize the documentation of elements of high geometric complexity common to the stylistic groups of the built cultural heritage that permeate the context of Fortaleza, Ceará, Brazil. The design of such a methodology is sought so that it can be used in restoration processes.

2 Methodology

The development approach for this work was divided into two stages. The first stage of analysis and planning, starts from the identification of the problem in the present paradigm of documentation of the built heritage, expressed in the difficulty of transposing geometric information in the registration processes. For this, photogrammetric capture and digital fabrication processes are incorporated to complementary fabrication processes aiming at the reconstruction of distinct materialities. With a reasonable understanding of the problems, tools and processes, we seek to develop organized workflows, in which we can classify a series of processes that operationalize the production of models and prototypes in accordance with the materiality of the object of study. The second stage seeks to validate the workflow propositions raised in the first, observing the feasibility of the application of these models in a local context, producing a series of prototypes in different materialities to evaluate different manufacturing techniques, observe the difficulties and potentialities of the processes, and record the results. Observing the particularities of the analyzed processes and the selected tooling, it was possible to outline a standard workflow for the production of physical reproductions of ornaments from digital models. The proposed workflow seeks, initially, to demonstrate the applicability in certain contexts and materialities. Besides obtaining the digital data, the process includes the reconstruction of the ornaments via digital fabrication, seeking to close a cycle of restoration steps for heritage assets so as to ensure a greater permanence for built cultural systems.

Observing the samples documented in the field, we sought to categorize them into common criteria related to the different materialities present in the ornaments of the included buildings. The categories that were considered as the focus of the scope of this work were: "cast metal", "wood carving", and "plaster". This classification has direct correlation to the manufacturing methods employed.

The techniques involved in the manufacturing processes most common to the different ornaments materialities observed are mapped in a flow chart where one can more clearly observe each step involved referring to each materiality.

To this flow chart is incorporated a device composed of a group of steps that range from the capture and digitization of the ornament's shape using photogrammetry techniques, to its rematerialization using digital fabrication techniques.

2.1 Capture and Fabrication Workflow

Photogrammetry using DSM was the primary technique used in the process of digitally capturing and reconstructing the artifacts. It operates by taking a collection of photographs taken from various angles of the target object as input and identifying correlations between groups of homologous pixels present in the provided photographs. The photos in different perspectives of the same object allow the comparative processing algorithm to spatialize the correlated pixels as points projected into Cartesian space. This aggregate of pixels is referred to as a "point cloud". According to Groetelaars (2015) The process of generating "point clouds" with the DSM technique can be divided into 5 main steps: (1) photo input; (2) automatic correlation of the photos; (3) reconstruction of the preliminary geometry of the object and camera; (4) dense association of homologous pixels; (5) creation of the geometric model as a " point cloud" and the Triangulated Irregular Network (TIN) mesh, which is a mesh of non-rectified triangles generated from the association of the vertices generated by the point cloud, which may be textured or not. As previously stated, the TIN mesh is generated by the associating vertices from the “point cloud” that are adjacent to each other to make faces. Given this process, the generated geometry is often overdetailed, making its file size sometimes too large to be handled efficiently for its proposed uses (i. e. documentation and digital fabrication). When that's the case, the process of remeshing comes as an optional step, enabling the creation of a simplified version of the 3D model, reducing the number of faces of the mesh while retaining as much detail as possible.

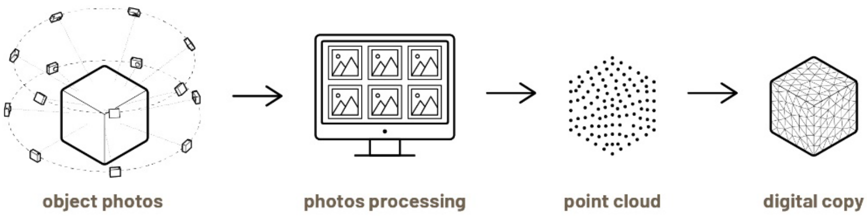

Figure 1. Diagram representing the main steps in a photogrammetry reconstruction. Source: Authors, 2022.

Acquiring a 3D model of the artifact allows for its use as a digital blueprint in processes of additive and subtractive manufacturing. Computer-Aided Design to Computer-Aided Manufacture software (CAD/CAM) can interpret the input geometry and output a series of machine-specific toolpath commands (this process is also known as "slicing"), these are known as G-code. Computer Numerical Control (CNC) machines such as CNC routers and 3D printers can receive G-code as input to produce physical prototypes of the original geometry.

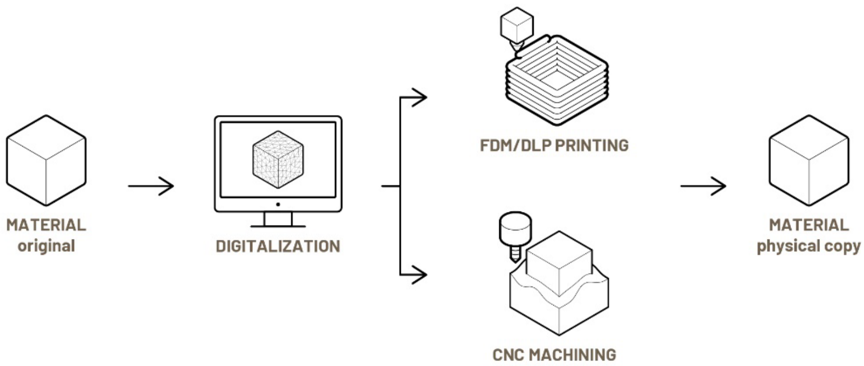

Figure 2. Diagram resuming the translation of a physical object's shape into a 3D model and rematerialization through digital fabrication. Source: Authors, 2022.

These digital processes were grouped and considered as a minor workflow path that allows for the translation of the artifact's shape through different materialities.

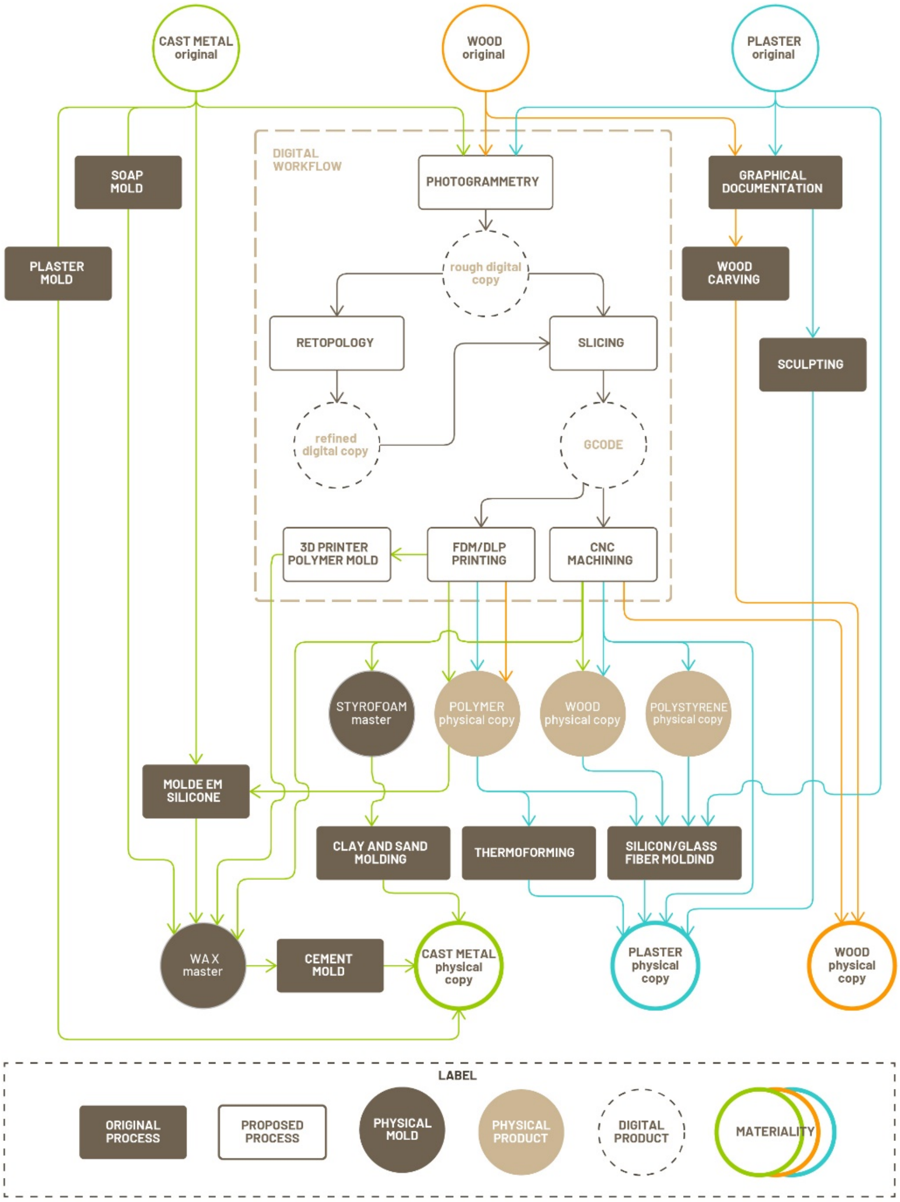

Figure 3. Flowchart mapping the possible pathways of processes involved in the translation of an artifact's shape from its original medium to a replica of the same materiality. Source: Authors, 2022.

Having all steps laid out (the digital processes together with the physical processes to produce replicas for the three materialities considered), possible workflows were elaborated in which the end goal was taking advantage of the digital device in the process of translating the artifact's shape from its original medium to a replica of the same materiality.

To validate the device elaborated by the merging of those previous workflows, a number of case studies were elaborated where a chosen sample of each kind of materiality would be subject to a series of processes mapped on by this device, wherein the goal is that the workflow meets two conditions: (1) the artifact is documented and replicated by the digital processes; (2) the final replica reaches the same category of materiality as the original one.

Limitations on the methods of fabrication available restricted the digitally manufactured replicas to be made mainly of polymers, polystyrene and wood. This means that to reach the end product, additional processes (i.e. lost wax casting, silicon molding, thermoforming, etc.) would need to be included in order to transpose the artifact shape to its proper final materiality.

3 Results

These samples were ornaments chosen from three different buildings as case studies in the scope of this work: (1) *Theatro José de Alencar* (Wood); (2) *Mercado dos Pinhões* (Metal); (3) *Farmácia Oswaldo Cruz* (Plaster). The criteria for their selection accounted for: ease of access, graphical complexity and how likely its photo-capturing were to result in a good 3D model.

3.1 Wood (Theatro José de Alencar)

Figure 4. From left to right: Photo taken from the ornament on the Teatro José de Alencar's door; The ornament's photogrammetric reconstructed model; 3D model of the isolated ornament; 3D printed replica. Source: Authors, 2022.

The chosen ornament for this case study was carved on the main access wood door from the "Theatro José de Alencar", that leads to the metallic internal structure of the theater. It is situated in Fortaleza, the capital of the state of Ceará, in Brazil.

Remarkable example of European imported iron architecture, the Theatro José de Alencar was built with the Glasgow firm *Walter MacFarlane & Co.* metallic structures, in its entirety made out of iron, supported by columns in cast iron that featured special design.

The chosen building fulfills the type of garden theaters and portrays the eclecticism in Fortaleza's architecture, emphasizing the art nouveau features. Having its doors open by the time of 1910 and registered in 1964 by the national government, through Decree 25 of November 30, 1937, as a protected heritage. (BARROSO, 2002)

As the ornament, which was worked on this step, the last segment of the construction was the settlement of the carpentry and frames, by the end of 1909. Most of the details are still preserved as the building has gone through some restorations.

The photogrammetry process sampled 45 photographs taken by a 12 MP cellphone camera, given the occasional absence of a professional one, and models were generated using the Epic Games Reality Capture v1.2. The results turned out convincingly similar to other captures, with minimal artifacts, and model cleanup was done separately in Blender.

A physical prototype was fabricated using 3D printing (ABS polymer) at a 1:2,5 scale. So far, the wooden prototype has not been manufactured yet.

3.2 Metal (Mercado dos Pinhões)

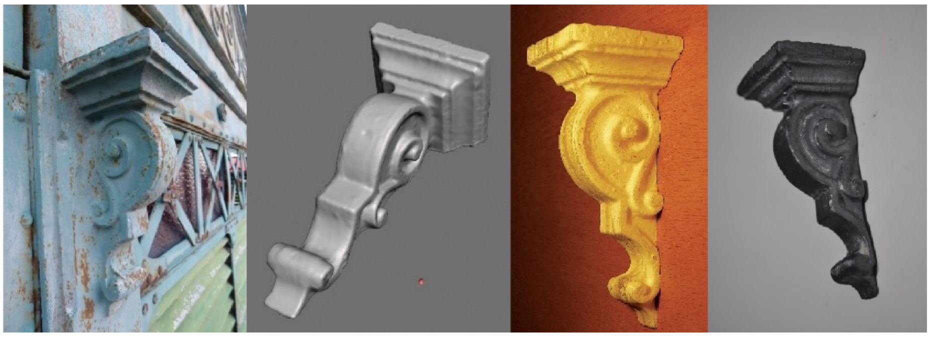

Figure 5. From left to right: Photo taken from the Mercado dos Pinhões ornament; The ornament's photogrammetric reconstructed model after cleanup; 3D printed replica; Lost wax cast metal replica. Source: Authors, 2022.

The Mercado dos Pinhões is a building registered as a Protected Cultural Heritage by the municipality of Fortaleza by Decree 12.368 of March 31, 2008. Originally, the metal structure was imported from France to be the first meat market in the city. It was made entirely of cast iron by the Guillot Pelletier workshop, which was also responsible for the structure of the Eiffel Tower. Inaugurated on April 18, 1897, it was one of several buildings built during the Belle Époque, a historical period marked by initiatives to "modernize" the province. In its first form, the "Iron Market" consisted of two pavilions connected by a central avenue and was located downtown in Waldemar Falcão Square.

With the construction of a new and more modern municipal market in 1932, the old "Iron Market" lost its strength. In 1938, the structure was disassembled and divided. One of the pavilions was moved and rebuilt in Marquês de Pelotas Square (also located downtown, but closer to its borders), where it remains to this day, gaining the name Mercado dos Pinhões. Currently, in addition to commercial activities, it hosts an extensive cultural programme overseen by the Fortaleza City Hall. The other pavilion has been relocated and rebuilt twice and is now located in the Aerolândia neighborhood (Filho & Sarmiento, 2003; Leal & Seligman, 2011). After abandonment for decades, it has recently been restored to house similar activities as its twin.

The ornament chosen is on the facade of the Mercado dos Pinhões, on the top of the pillars outside the building.

The photogrammetry process sampled 37 6MP photographs and models were generated using three different software (Agisoft Photoscan, Autodesk ReCap, and Autodesk ReMake), all yielded similar results. Model cleanup was done separately in Autodesk Meshmixer.

Physical prototypes were fabricated using 3D printing (PLA polymer) and CNC milling (Styrofoam, Wax, MDF). The 3D printed prototype was later used to produce a silicone mold to make wax copies. The final metallic piece was produced using lost wax casting using a mold in 1:2 scale.

This case study is described in further detail in “Documentation and digital fabrication methods for restoration of eclectic metal ornaments” (MOREIRA et al. 2017).

3.3 Plaster (Farmácia Oswaldo Cruz)

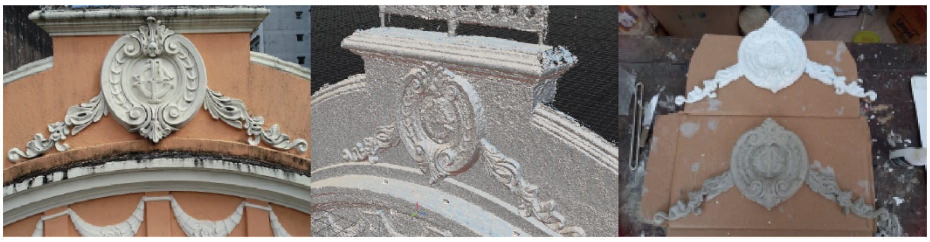

Figure 6. From left to right: Photo taken from the Farmácia Oswaldo Cruz ornament; The ornament’s photogrammetric reconstructed model; 3D printed replica (top) and silicone molded plaster replica. Source: Authors, 2022.

The building is described on the institutional site of the Secretary of Culture of the State of Ceará (SECULT-CE) as follows:

The pharmacy was built in the eclectic style, in the first half of the 20th century, the pharmacy occupied a prominent position in the commercial area, located in the middle of Praça do Ferreira, a place of cultural and social effervescence at that time. There, for a long time, until the 1970s, there was the custom of meetings on the sidewalks of the most varied groups, to discuss various topics, ranging from the trivial to the erudite, and where the famous "booing at the sun" took place, which is part of Ceará's anecdotes.

The building reflects, through its ornate facade and the mix of decorative elements, the restlessness of an architecture in search of a new language, which emerges in eclecticism as a way to revive the old architecture, but with the use of new technological advances of nineteenth-century engineering (FORTALEZA-CE, 2015).

The chosen ornament was the crowning of the facade, whose hard-to-reach position above the first floor presented a good testing opportunity for using drones as a photographic capture tool. The photogrammetry process sampled two sets of photographs (180 and 257 photos) sampled from 4k 60fps videos taken by a DJI Phantom 4 Pro drone equipped with a 20MP camera. The 3D model was generated using RealityCapture v1.2.

The original model captured most of the building facade and had approximately 26.3 million triangles, this model had some surface noise, and its size was unhandy, so it was cropped, smoothed and remeshed into four different versions (3M tris, 1M tris, 100K tris and 10K tris each). The 1M tris model was chosen for prototyping, since it was the one with less geometry that still maintained most detail. The ornament was isolated from the model using boolean operations in Blender and exported for slicing. Physical prototypes were fabricated using 3D printing (PLA and ABS polymers) and CNC milling (Styrofoam, XPS). The 3D printed ABS copy was later used to produce a silicone mold to make plaster copies.

The main issues found through this case study were:

- The photogrammetric reconstruction generated surface noises that affected the physical accuracy of the model, it’s unclear if the photo sampling hasn’t covered enough angles or if the photos taken by the drone while moving had motion artifacts.
- FDM printing generated stringing on the printed piece (this can happen especially when printing ABS and PETG), this can negatively affect molding processes and make clean-up time consuming.
- The silicon molding was inconsistent, which made artifacts that could affect the final piece.

4 Discussion

This study has allowed an exploration of the possibilities presented by the development of a methodology for documenting elements of high geometric complexity. Techniques such as photogrammetry and 3D scanning reveal complementary possibilities to these processes of documentation and registration, as the form of the registered object is transposed to digital media.

Higueras (2021) reinforces this by explaining that obtaining 3D virtual models with metric accuracy in relation to the original measurements has several applications in the field of cultural heritage. These applications range from documentation, research and promotion of cultural heritage to its reconstruction, virtual reintegration and 3D printing for its reproduction and physical reintegration.

4.1 Practical application possibilities

The main possibility explored with the incorporation of the processes in this research was the manipulation of obtained 3D models as visual aids or on the process of fabricating physical prosthesis to be used in restoration projects (NOGUEIRA et al., 2019; AMORIM, 2022).

Experiments in producing these prosthesis often rely on the presence of symmetry and repetition in the documented artifact. This way speculation on the original shape of the ornament is more easily avoided and a 3D model can be produced using a model of a damaged area and an undamaged one, this way a boolean difference operation could be performed, where a digital model acts as a geometric operator, detecting another model that intersects with its geometry. The operator is used as a reference to construct a solid model, which is composed of the junction of the faces of the geometry of the operated object that do not intersect with the operator, and the geometry of the operator that intersects with the operated object. This process generates a fragment based on the reference model, which fills the negative space of the model (HIGUERAS et al., 2021; HENRIQUES et al., 2020).

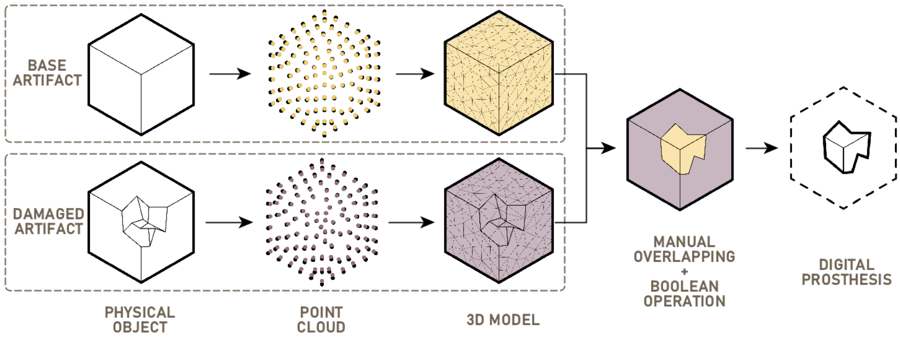

Figure 7. Diagram representing an artifact prosthesis produced through boolean subtraction using 3D models of a damaged artifact and a base that's symmetric to it. Source: Authors, 2022.

4.2 Quantitative Analysis

A workflow such as the one described in this work, encompassing many different processes and tools, is bound to have results of varying qualities, and serves mostly as a general guideline through the steps available. Its exploration, however, opens a path to the qualitative evaluation of the techniques and tools available, as well as different workpaths, pertaining to the recording and replicating of built cultural heritage.

Scopigno et al. (2015) produces a survey which presents a summary table of fabrication techniques for cultural heritage, precision, and working size. Expanding this method of analysis to encompass different work paths might be an option when producing a more thorough workflow.

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