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The possibilities of making copies of wooden historical objects by CNC milling based on digital three-dimensional models

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Abstract

Among people working with cultural heritage objects, the ability to make the best possible copies has always been one of the important topics. In recent years, the development of techniques that make it possible to make three-dimensional documentation of heritage objects and the capabilities of software that controls cutter machines have made it possible to make material copies in wood, among other things. Unfortunately, the lack of standards for the creation of three-dimensional documentation, as well as the relatively unique nature of this type of release, translate into a lack of common understanding of the real possibilities and limitations of these technologies. What is needed is an analysis of the path of execution of this type of project, which would discuss the planned exhibition or educational goals, the assumed technological parameters achieved in the course of implementation and an evaluation of the results achieved. The accumulation of such results will not only help facilitate the implementation of future projects, but will also be the first step towards the creation of standards and quality norms for this type of product.

Introduction

Today we have access to a number of technologies for the three-dimensional documentation of works of art (ToF time-of-flight scanning, scanning with structured light, photogrammetric techniques, etc.). The result of using these measurement techniques and data processing methods can result in very different digital products. We also have many areas of possible use of three-dimensional data in institutions engaged in protection and research of material cultural monuments. In the "Glam 3D" project - carried out by The Engelberg Center on Innovation Law & Policy NYU School of Law, defined the following four scopes of application: Iinteractive display, Analysis and measurement, Creating physical replicas from the Skurce and Documenting physical changes in a cultural resource over time.[1]

Very few employees of cultural institutions are aware of what digital products they need in order to be able to implement the research or popularization. Many museum institutions do not have their own laboratory's making three-dimensional documentation and have to outsource this kind of work to external companies. It is very difficult to properly plan the process involved In creation and use of three-dimensional documentation without access to standards, that would clearly define the minimum quality requirements and methods of quality verification for individual digital products.

Studies such as "Copy Culture. Sharing in the Age of Digital Reproduction" by Brandan Cormier, give a comprehensive introduction to the world of digital documentation and the possibilities of using three-dimensional data - but they do not provide specific quality parameters. The oft-used phrase "high quality" is defined here as follows "High quality means a level of quality sufficient to constitute a representation of a Work as faithful as possible." [2]. Explaining this concept further [3] we have a reference to specific scanning devices, but with no scanning spatial resolution given for any of the examples shown. Such a comparison illustrates well the problem that not every scan and the model created based on it will give us the level of data we need but does not answer the question of what that level of data should be.

Nowadays we have access to numerous positions in which it has been analyzed in detail how three-dimensional data should be preserved, stored, described with metadata and according to what rules we should share them. Still we have no answer to the question - what quality of 3D data should be produced to optimally meet the requirements of a specific application. It can be assumed that if we use the most accurate measurements, for example, by scanning with structured lighting with a spatial resolution of 2500 points per mm^2, then the quality of the produced data will cover all ranges of applications in which we will need shape data. This approach for many scopes of applications will generate huge amounts of redundant data, and it is also so costly that only a few institutions will be able to use it in their day-to-day operations.

Studies such as "Basic principles and tips for 3D digitization of tangible cultural heritage - for cultural heritage professionals and institutions and other custodians of cultural heritage", prepared by the European Commission's Expert Group on Digital Cultural Heritage and Europeana [4] do not solve this problem either. This valuable document organizing the process of planning and implementing a digilization project teaches how to ask questions - but does not provide concrete answers.

Over the past several years, efforts have been made to match optimal documentation techniques and corresponding equipment to the documentation of particular groups of historic objects. Today we know that sometimes the creation of adequate documentation requires a combination of several methods, and that more important than the parameters of the equipment used are the quality parameters of the digital file, which is the result of the documentation process. If we read today's five-point list of "The basic principles at a glance," then in the first point we will have to decide why a certain type of documentation is created, in the second point to determine how we will use the results of the process and only point 8 concerns the equipment and its proper use in the project. [5]

For this reason, employees of cultural institutions need to describe digital products that will provide a satisfactory end result in a given field of application. Finding solutions that guarantee the best possible end result requires the cooperation of specialists from many fields. Hence the difficulty of creating such comprehensive studies. The following analysis deals with the application of three-dimensional techniques in only one specific field of application - milling in wood. To show the complexity of the topic of "three-dimensional documentation", let's note that, for example, in a completely different direction goes the development of software for three-dimensional visualization, using artificial intelligence (solutions such as NeRF - neutral radiance field, or ADOP - approximate differentiable one-pixel point rendering) in which the product is not at all a spatial model in the form of a grid of triangles or a point cloud. The whole focus in these processes is not on the correct representation of geometry, but on creating a photorealistic three-dimensional visualization.

Research problem

On the basis of an analysis of two projects related to the making of physical copies of historical objects through digital milling in wood, an analysis was made of what digital product is needed for such realizations. Determining the precision with which we are able to copy the selected geometry requires describing the factors that will affect the decrease in the quality of reproduction at different stages of the project. The purpose of the analysis is to try to define the minimum quality requirements for a digital file and to determine the mapping quality that can be achieved. This will allow, on the one hand, to assess whether the digital documentation created is good enough to take advantage of the capabilities of wood milling technology, and on the other hand, whether we are not creating redundant data that will be lost anyway at the level of making the physical model.

Exemplary realizations

Each time trying to propose a synthesis, it is good to be able to refer to as diverse material as possible. The basis of the non-union study is only two projects but with very different specifics.

In the first case, the idea was to make a scaled-down (1:2 scale) material copy of a valuable sculpture for educational purposes. The original statue, which is part of the crucifix, is an object of worship and is located deep inside one of the chapels in Warsaw Cathedral. For this reason, access to the original is difficult. In the second case, we have an object with a more schematic geometry which was to be duplicated for display purposes. The idea was to make copies of twelve benches that could be inserted into the historic interior of a residential museum. They were to fit stylistically into the surroundings, so as not to interfere with the impression of immersion - immersion in the atmosphere of the historical interior of several hundred years ago. Due to their function - they were to be a resting place for visitors to the painting gallery - they could not be original historical objects. Making contemporary material copies modeled on historical material seemed a great solution. In order to reduce the factor of subjective interpretation that the making of a sculptural copy always introduces - it was decided to use digital CNC milling.

The example objects and their three-dimensional measurements

The first object is a full-plastic sculpture depicting the Crucified Christ from the Baryczka Chapel in Warsaw Cathedral. The sculpture was probably created in Nuremberg in the first quarter of the 16th century.[6,7] It was made in linden wood. The height of the Christ figure is 200 cm and the arm span is 175 cm. The sculpture is one of the most valuable monuments of late Gothic sculpture in Warsaw and a very important object of religious worship. Three-dimensional measurements of the sculpture and a 1:2 scale copy of it were made at the request of the Museum of the Archdiocese of Warsaw. The idea was to be able to conduct classes in art history and stylistic analysis not in the interior of the temple, but in the museum rooms, using a copy that reproduces the geometry of the original as closely as possible.

***Figure 1**. Sculpture of Christ from the Baryczka Chapel, Warsaw Cathedral, 2021, photo by P. Plewa*

***Figure 2**. Nineteenth-century oak bench from the King John III Palace Museum in Wilanó, 2020, photo by A. Indyk*

The hair of Christ, which is not made of wood, has not been the subject of reconstruction work. To this day, the museum has not decided whether a polychrome imitating the original should be reproduced on the surface of the copy.

The three-dimensional model was made by combining photogrammetric techniques with data acquired through structural scanning with a spatial resolution of 100 points per mm2.

The second object is a wooden bench (museum inventory number Wil.3207) from the collection of the King John III Palace Museum in Wilanów dating from the middle of the 19th century (before 1877) and made in oak wood. The bench measures 172.0 cm by 53.5 cm by 40.5 cm. Three-dimensional documentation was created only for the carved legs, as the seat of the bench was to be made from a simple oak plate. The carved decoration of the bench consisted of a support element and a second set piece placed on the plate that was the seat. The dimensions of these elements were 38 cm by 34.5 cm by 5 cm (width, height, thickness) and 40 cm by 11.5 cm by 5 cm.

Based on the analysis of the implementation of the various phases of the completed work, we can list the following factors that affect the final quality of the reproduction of the physical model. These factors will be the sum of errors and technological limitations included in the two main phases of the activity - that is, the creation of the digital model and the stage of digital milling in wood.

***Figure 3**. Christ figure from Baryczka Chapel, three-dimensional model in the form of a triangle mesh, visualization by P. Zajdel.*

***Figure 4**. The lower carving element of the oak bench, a three-dimensional model in the form of a triangle mesh, visualization by E. Bunsch*

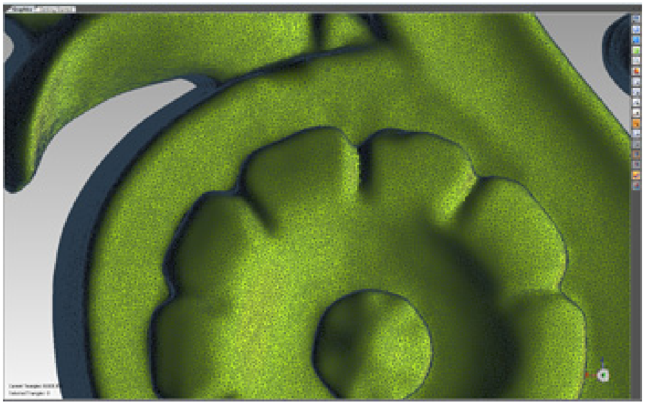

***Figure 5**. The lower carving element of the oak bench, a three-dimensional model in the form of a triangle mesh, close-up of a detail, visualization by E. Bunsch*

The stage of creating the 3D model consisted of three major steps:

1. Collection of measurement data (where the quality of the surface representation will result from a combination of two parameters - spatial resolution of the data and measurement uncertainty).

Any inaccuracy at this stage will be echoed throughout the subsequent manufacturing process. Another limiting factor is the level of detail the scan can capture. In the case of complex antique models with very fine details, these elements may not be accurately captured or may exceed the resolution capabilities of the scanning equipment.

The two carved bench pieces were scanned on a robotic measuring station equipped with a structured light scanning head with a spatial resolution of 100 points per mm^2. For example, 43 directional measurements (having an average of about 1.2 million measurement points) were taken for the lower bench piece. The permissible measurement error for these measurements was 91 µm for sigma3 (sigma 3 covers 99% of the measurement results while the sigma 1 parameter is often used in technological descriptions referring to only 66% of the results. In the case of our measurements, the sigma 1 parameter was 31 µm). The final model in the form of a triangle mesh made for the lower carving element of the bench has 8 million triangles. Based on this data, the carving elements needed for the 12 benches were milled in oak wood. The mapping scale here was 1:1.

2. Measurement data processing - creation of a three-dimensional model

At this stage, the individual directional scans must be combined into a single model.

3. Processing of the model into a form supported by the milling device.

The process of decimation and optimization of the 3D mesh can further increase these tolerances, leading to a greater degree of deviation from the original geometry of the model.

a. Toolpath tolerances: Generating an optimal tool path is a complex task. If the tool path is not calculated accurately, the milled model will deviate from the scanned model. Tool paths must also take into account the limitations of the tool's geometry and motion, which can cause further deviations. High-quality CNC machines can maintain tolerances as tight as 0.01 mm (military-grade tolerances), but tolerances of 0.1 mm to 0.05 mm in a well-controlled environment are more typical.

b. Toolpath optimization: A suboptimal tool path can lead to longer milling times, lower quality of the milled surface, and even tool breakage. Tool path optimization can depend on many parameters, including model geometry, material type, milling speed, feed rate and cooling conditions. Good optimization can improve surface finish and precision, potentially improving tolerances by as much as 0.03 mm for wood.

c Interpolation by CAM software: CAM software uses interpolation to convert the geometric information of a 3D model into a series of discrete motions for a CNC machine. The accuracy of this interpolation can affect the fidelity of the milled model to the original 3D scan. The more complex the geometry, the more difficult it is for the software to generate an accurate tool path. This is especially difficult for curves and surfaces that cannot be perfectly mapped using linear or circular interpolation. High-end CAM software can achieve very high accuracy, often down to 0.01 mm, but it is not unusual to experience deviations of up to 0.1 mm due to interpolation errors.

The milling stage

Limitations at the milling process level:

1. Wood as a living material: Wood, being an organic and "living" material, retains its sensitivity to environmental changes even after harvesting and processing (including drying). Milling often disrupts the internal balance of wood fibers, which can lead to distortion or warping. These distortions usually result from the release of internal stresses during milling or changes in atmospheric conditions such as humidity and temperature.

The severity of these problems can be greater when the direction of the wood grain does not coincide with the main axis of the piece, or when there are differences in grain direction, such as knots, in the piece. The extent of these distortions is influenced by many factors, including wood species, moisture content, grain orientation and part geometry.

Given the variability of these factors, providing an exact tolerance range is difficult. However, as a general estimate, these factors can lead to deviations of several millimeters along the length of the part. For example, a deviation of 1-2 mm over a span of 1 meter can be expected, depending on specific conditions and wood properties.

2. Minimum ball mill size: The smallest details that can be ground are determined by the size of the ball mill used. A smaller ball mill can produce finer workpieces, but it also takes more time and is more prone to damage, which increases costs. If the workpiece is smaller than the radius of the ball mill, it will not be finely ground. Commercially available ball mills can go down to a radius of 0.1 mm (mainly for engraving metal and small details), but in general for wood, a radius of 1 mm to 0.5 mm is the smallest practical size for reliable performance and reasonable cost.

3. Mounting method and application of force: In 4-axis CNC machining, the mounting method can significantly affect the final result. If the material is clamped axially and clamping forces are applied longitudinally, this can lead to bending of the workpiece, especially if the material becomes thinner after milling. This is especially true for wood, which is relatively flexible and prone to deformation. The exact tolerance can vary widely, but in the worst cases it can be as small as a few millimeters, especially for longer and thinner parts. To mitigate this issue, a combination of strategic measures should be taken at both the design and milling stages during model reconstruction.

4 Milling access limitations: The geometry of the part being milled is limited by cutter access. If the geometry of the part has deep recesses or undercuts, they may be difficult or impossible to reach with a standard milling configuration. In addition, the angle between the cutter and the milled surface can also affect the quality of the milled surface. This limitation will depend on the exact geometry of the part and the length and shape of the cutter, but it is not uncommon for these access limitations to result in deviations of several millimeters in some areas of the part.

5 Type of CNC machine used: The number of axes on a CNC machine can significantly affect the ability to accurately reproduce a scanned model. A 3-axis machine can only mill geometries that are accessible from above, while a 4-, 5- or 6-axis machine can mill more complex geometries, potentially from any direction. However, even with a multi-axis machine, there can be limitations in terms of the reach of the cutter and the risk of collision with the part or the machine itself. Tolerances achievable with multi-axis machines can be as good as with 3-axis machines (i.e., in the range of 0.01 mm to 0.1 mm), but only if the part geometry is within the machine's capabilities.

For sharing his knowledge of woodworking possibilities and for his detailed analysis of the milling process and its limitations, I would like to thank Mr. Patryk Zajdel of Viktor- Art. Pracownia Rzeźbiarska.

Figure 6. *Made using CNC milling, a copy of the bench in the gallery of the Wilanów Palace,photo by E. Bunsch*

In the case of creating a physical model of the carved bench pieces, a triaxial milling machine was used, with the pieces being milled on both sides and their edges machined by hand carving. The process of the milling itself was carried out in three phases: first with a flat milling cutter with a diameter of 10 mm, then with a spherical milling cutter with a diameter of 4 mm (with a coverage of about 80%), and the final alignment was carried out with a V-shaped milling cutter with a diameter of 05 mm. Due to the character of the material, i.e. hardwood, during milling the cutter sometimes worked across the direction of the grain of the wood (this is not how a man operating a chisel would work by hand), and in these places the surface of the wood was gently ragged which made it necessary to make manual corrections after milling. It can be estimated that in the case of these carving elements, human intervention after milling required about 40% of the surface, and the subjective modifications introduced at this stage resulted in a departure from the original shape by about 0.5 to 1 mm. (For the information on the milling of the bench elements, I thank Mr. Tomasz Majcherk and Mr. Piotr Majek).

In the case of the milling of the Christ figure from the crucifix in the Baryczka Chapel, the chosen wood species made it easier. Linden, as a soft wood, lends itself much better to the milling process. Therefore, in this case it was decided to leave the surface of the sculpture without any carving corrections.

Figure 7. *Copy of Christ sculpture made by CNC milling in linden wood (without any hand carving corrections), photo by E. Bunsch*

Some details of the original object even captured by us at the level of the scanning and model making process will be lost at the milling stage. This refers, for example, to the very notches made by a wood carving artist using chisels, which in cross-section have the form of sharp triangles. Even the thinnest milling tip will not be able to reproduce such a shape. In such a situation, we may choose to leave this slightly altered geometry, assuming that the perceptual difference for most viewers will be imperceptible. Or we can choose to use hand wood chisels after the milling process and "correct" the geometry in key areas. We will then achieve a surface shape consistent with the original one, which is the result of the work of a particular tool. However, we must be aware that we have just decided on another subjective interference with the copy being made. Another compromise. Compromises are unavoidable in such a complex technological process. The whole problem is to make the related decisions consciously.

Conclusions

When evaluating the described errors and inaccuracies, we must keep in mind that some of them relate to differences in the geometry of entire large elements of the milled object, and some relate to the quality of the reproduction of the detail at the local level. The scale at which we will make the physical model is important, that is, what will be the ratio of the size of the model being made to the original monument. If we will reduce the size of the physical model, we can get good milling results even using a model with less than ideal spatial resolution. On the other hand, if we want to create a physical model enlarged in relation to the original - then we will have to use a scanning method with a higher resolution, for example, 400 or 1600 points per mm2, in order to achieve a good result.

However, for most applications that envisage making a copy by milling in wood, we can assume that the total error rate of the prepared three-dimensional model should be characterized by a range of 0.1 mm to 0.3 mm.

The examples given clearly indicate that the technological process in question is not an ideal solution. However, before we dismiss it as a helpful solution and start treating it only as "playing with technology" let's consider what limitations the existing methods of creating physical copies of historical objects are subject to. It will then turn out that even this still imperfect technological path allows us to make copies in wood more accurately, faster and cheaper than ever before.

References

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[2] "Copy culture. Sharing in the Age of Digital Reproduction" by Brandan Cormier (ReACH Reproduction of Art and Cultural Heritage) London 2018, pg.2

[3] ibidem, pg 57

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Author Biography

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