DIGITAL MODEL GENERATION STRATEGY FOR PRINTING MINIATURIZED REPLICA OF HISTORICAL CAST IRON OBJECTS – A USE CASE STUDY

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Abstract

The Cast Iron Museum at Sayn (Germany) hosts a wide range of historic cast iron objects ranging from highly detailed fly-size figures to oversize eagles and church bells. Replicating the historical cast iron, i.e. free formed objects, as miniaturized 3D prints for a new exhibition requires scanning to create the digital model.

High quality of the digital model is a fundamental prerequisite for the production of the miniaturized 3D print. The influence of software selection and settings during data preparation from point cloud, mesh and finally solid is highlighted. Printing process selection is the final step in achieving the required print quality.

A scanning and model generation strategy is developed and described using several exemplary objects from the Sayn Museum. The final print quality resulting from the selected scanning process is evaluated.

Motivation and Object Selection

The Iron Foundry at Sayn (Germany) dates back to 1769. In 1815 the Prussian State and later in 1865 Alfred Krupp[1] took control. Various cast iron goods have been produced ranging from industrial applications (guns, church bells, etc.) to household products and fine arts goods. The roof of the casting hall itself rests on load carrying cast iron structures.
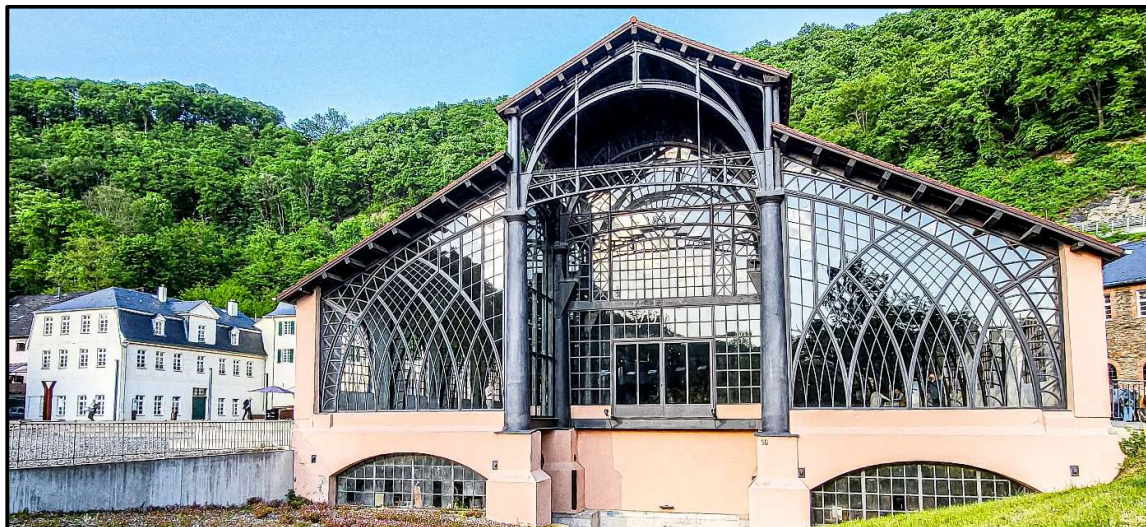

Figure 1: Casting hall (front view) of the Cast Iron Museum at Sayn

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[1] Alfred Krupp (1812 - 1887) German industrialist and inventor

Figure 3: (a) "Sayner Mücke" ("Sayn Fly"), (b) Statue of Napoleon (height approx. 25 mm), (c) Bust of "Elisabeth" (height approx. 35 mm), (d) Bust of "Benedicta von Löwendal" (height approx. 800 mm)

Figure 2: (e) Garden Chair by Karl Friederich Schinkel [4], (f) Vase (diameter 740 mm, height 900 mm), (g) Church Bell with inscription "Sayner Hütte" and ornament of Prussian Eagle (bottom diameter 1250 mm, height 1200 mm), (h) Prussian Eagle (wingspan 1050 mm)

The foundry was closed in 1926, but after the restoration started in 2004 a Cast Iron Museum was established hosting a wide range of original objects. For 2023 a new exhibition was planned "3D Printing Meets Iron Art Casting" for which miniaturized replica of these objects were needed. Except for the "Sayn Fly"[2] all listed objects were scanned and printed. Practical experiences from scanning the bust of "Benedicta von Löwendal" (d), Chair by Schinkel[3] (e), vase (f) church-bell (g) and eagle (h) result in case-specific strategic model generation rules.

State of the Art

A **strategy** is a plan of action designed to achieve a long-term or overall aim. Scanning free formed objects with the task to produce miniaturized prints for an exhibition requires such a plan. The simple plan "scan – slice – print" has to be detailed and fundamentally improved to lead to success.

A **digital model** is the absolute prerequisite for manufacturing objects additively. The quality of the digital model is therefore decisive for the quality of the printed part and its creation is part of the Additive Manufacturing Product Development Process (AMPD process).

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[2] "Sayner Mücke", cast from only one drop of molten iron, weight 0,27 gr., legs were made from steel wire
[3] Karl Friedrich Schinkel (1781 – 1841), Prussian building official, master builder, architect and designer

The current AMPD process consists of four steps: product planning, product design, work preparation and product manufacturing [1].

According to Auth [1], work preparation covers the pre-process of AM whereas product manufacturing covers the in-process and the post-process of AM. For designing a new technical object, a **modelling process** is used by 3D CAD modelling with an optional topology optimization. The created volumes and shapes are based on simple (primitive) analytically defined, i.e. exact, geometries. Topology optimization may create free formed surfaces defined by splines. The digital model is defined during the product design phase. Replicating does not require a planning and a design phase, since the object already exists.
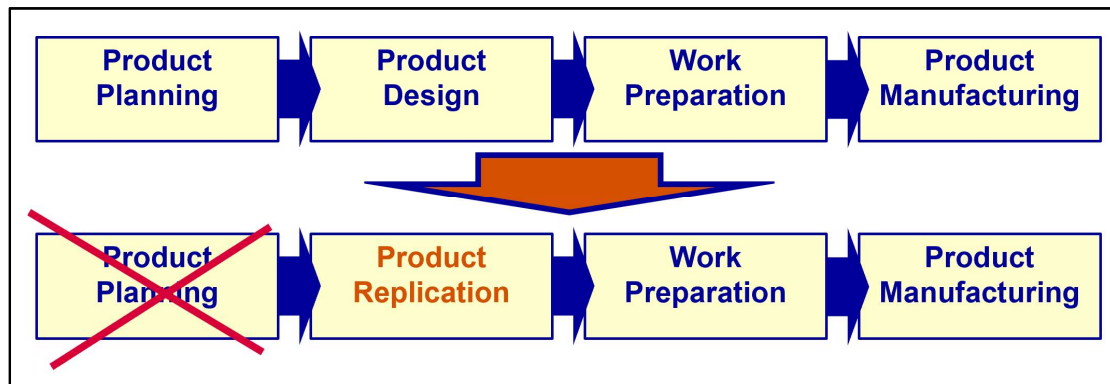

Figure 4: AM process and modified AM process

Replicating existing objects with free form surfaces requires a **scanning process**. Scanning produces a point cloud which is transformed into a surface model by meshing creating an STL-file. The solid is then the base for slicing and printing. The detailed description of the replication process will identify the individual steps to be taken and highlight parameter settings and methods leading to an optimal digital model. The final quality depends on parameters within the process which can be influenced only within certain limits. The steps of the replication process and their significance to the final print quality are highlighted and discussed.

The complete **replication process** has two steps: scanning and modifying. The modification step may be detailed into repairing and refining. Repairs are modifications to the
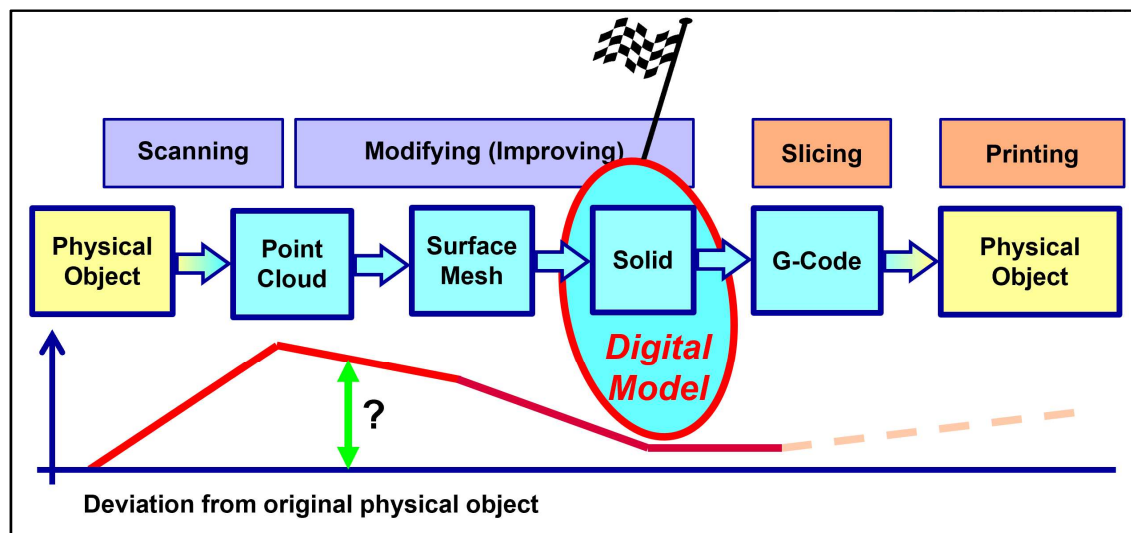

Figure 5: Replication process

model which are necessary to print the model. Refinements are modifications bringing the surface geometry as close to the original as possible. However since no original digital model exists, no quantitative measurement of the model´s deviation from the original is possible.

Slicing and printing are part of the replication, but the digital model is fully defined after all modifications

Scan Process

To execute the scanning process **hard- and software** are important items which have been selected beforehand. Object size and scanner resolution are the leading parameters. For scanning the bust of "Benedicta", chair, vase and eagle a "Shining EinStar 3D" handheld scanner is used. It is connected by cable to a "HP ZBook vPRO" with an Intel Core i7 processor and two graphics cards (one Nvidia Quadro M100M and one Intel HD Graphics 530) to allow fast processing of large amounts of data. The ZBook also hosts the Shining proprietary scanning software "ExStar" which controls the scanning process and allows displaying the point cloud and meshing the point cloud into an STL-format. Modifications will be done in "ExStar", Autodesk "MeshMixer", Artec "GOM Inspect", "Fusion 360" as well as Dassault Systèmes' "Solid Works".

The "Shining EinStar 3D" is a structured-light handheld scanner equipped with two stereo cameras, one RGB camera and an infra-red VCSEL Laser (Vertical Cavity Surface Emitting Laser) structured light source. The object is fixed and the scanner is moved around the object making it suitable for large static objects. Resolution will reach 0,1 mm point distance. Structured-light scanners project a precisely calibrated pattern (parallel lines, stripes or a grid) onto the surface of the object. The corresponding pattern is distorted when it hits the object. The pattern is captured by the scanner's built-in stereo cameras in a high-frequency scan and processed by the integrated scanning software through active triangulation. Due to the defined positions of light projector and cameras, the coordinates of each single surface point can be precisely calculated. Data of the RGB camera allow determination of each point´s color. Structured light scanning allows objects to be captured in the sub-millimeter range without touching them. [2]

Figure 6: "Shining EinStar 3D" Scanner (left [5], middle), distorted light pattern (right [2])

Result of the scanning process is an ASCII file containing the coordinates of each point of the point cloud which is displayed in the "ExStar" software. Each single point of the cloud is visible. The point cloud is an incomplete representation of the physical object due to scanning faults, missing surface between the points and the non-solid character. Modification of the model by manipulating single points in the ASCII file would be tedious and ineffective.

However, it is the starting point for all further modifications leading to the optimal digital model with the least possible deviations from the original object.
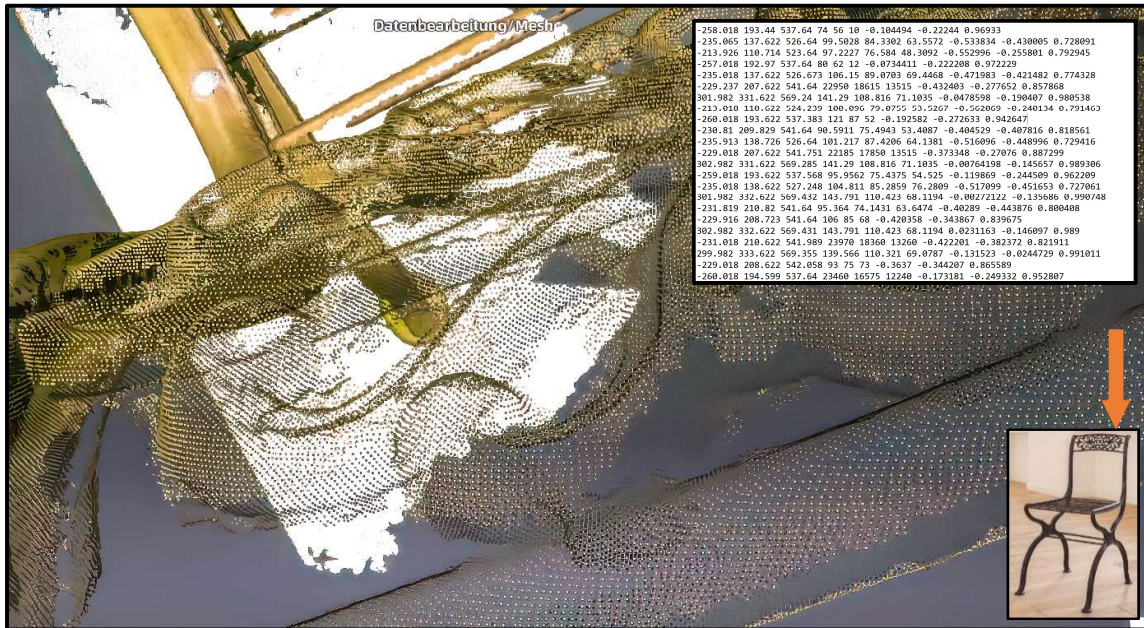

Figure 7: Point cloud - view of the back of the chair from above and extract from ASCII file

Cast iron surfaces are rough. When scanning large areas, e.g. the bell or the vase operators tend to scan the same area multiple times to be sure to catch every detail of the surface. Each time different points will be scanned. As a result, the point cloud files become huge. File sizes of several GBs were experienced.

Figure 8: Typical cast-iron surface of the bell (left,), optical feedback when scanning the cast iron surface of the bell (right), [14]

Point Cloud Modification

The scanning step has been completed with the creation of the point cloud, all further repairs and refinements are listed below. The necessity of repairs becomes evident by the integration of some automatic modifying functions in the scanning software "ExStar". The following table highlights the possible combinations of modifications and the manual respectively automatic routines provided by the available software packages:

Modification		ExStar	Mesh Mixer	GOM Inspect	Solid Works
Transformation into meshed surface (STL)	automatic	X			
Closing of holes / gaps	automatic	X	X		
	manual		X		
Removal of floating parts	automatic	X			
	manual		X		
Smoothing of surface	automatic	X			
	manual		X		
Adding analytically defined geometry	manual		X	X	
Replacing Elements	manual		X		X
Define origin	manual			X	
Align with horizontal plane	manual			X	

To allow easy modification the cloud is **transformed into a meshed surface**. The individual points of the cloud are connected to form triangles:
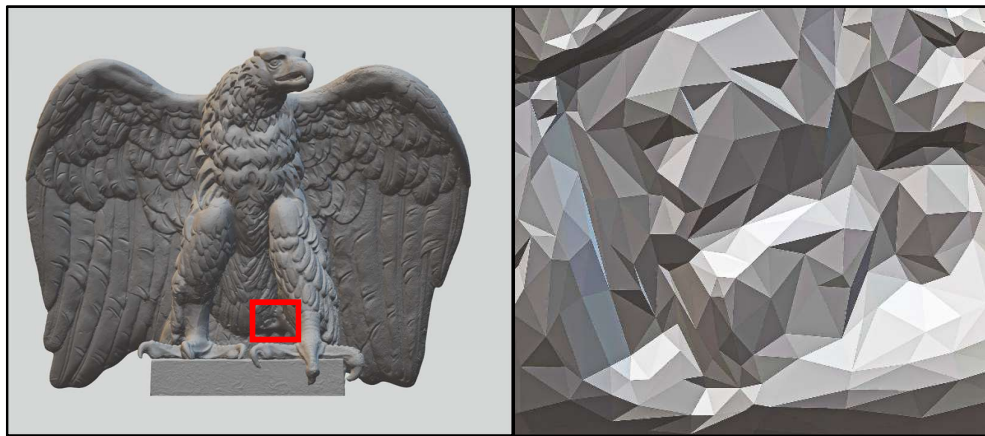

Figure 9: STL of the eagle (left) enlargement of the triangles forming the surface (right)

The triangle mesh only approximates the real surface of the object, a deviation from the original is evident. A large number of triangles will result in a more detailed surface model (closer to the original) and is desirable. "ExStar" allows a maximum number of 20 million triangles in the mesh, leading to large STL files and meshing times between a few minutes and more than 24 hours depending on the size of the input file. The number of triangles can only be selected at this point and will have to be considered carefully. Two small exemplary point cloud files were meshed with all parameters set to minimum values and results noted:
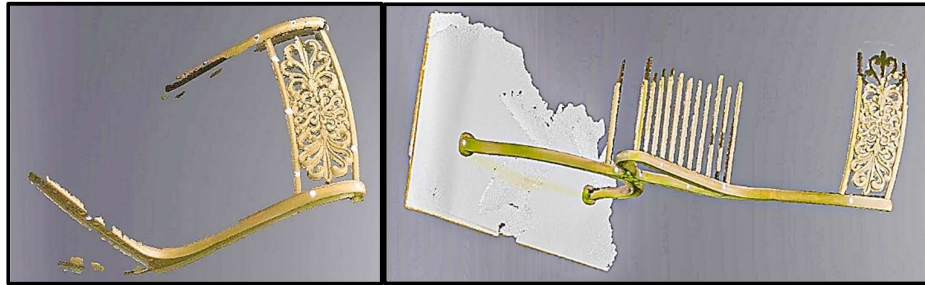
Figure 10: Exemplary point cloud files, 8276 KB (left: small) 53913 KB (right: large)

Size of input point cloud file	Max. number of triangles	Size of meshed file	Meshing time
8276 KB	20.000	974 K	60 sec
8276 KB	200.000	9759 K	105 sec
8276 KB	2.000.000	187960 K	140 sec
53913 KB	20.000	981 K	100 sec
53913 KB	200.000	9763 K	125 sec
53913 KB	2.000.000	97654 K	235 sec

The results are as expected: meshing times and STL-file sizes rise with original file size and maximum number of triangles. Therefore, large input files will increase meshing times and STL-file sizes.

Closing of holes and gaps, floating parts removal and smoothing of the surface are integrated automatic functions of the "ExStar" meshing routine. Gaps and holes are areas where the distance between points of the cloud becomes too large to be connected to the next point. These can be detected and closed automatically but the large point distance will result in an imprecise approximation. "ExStar" offers three basic meshing qualities ("Non-Watertight, Semi-Watertight and Watertight") and a range of optimization options. These options include smoothing of the mesh, removal of floating parts, filling of small holes and the removal of spikes. Filling of large gaps or holes may exceed manual skills. However, the final consequences of an automatic repair of such a point cloud fault becomes evident in the model and the printed eagle. Adding more points should be seriously considered. However, the scanner
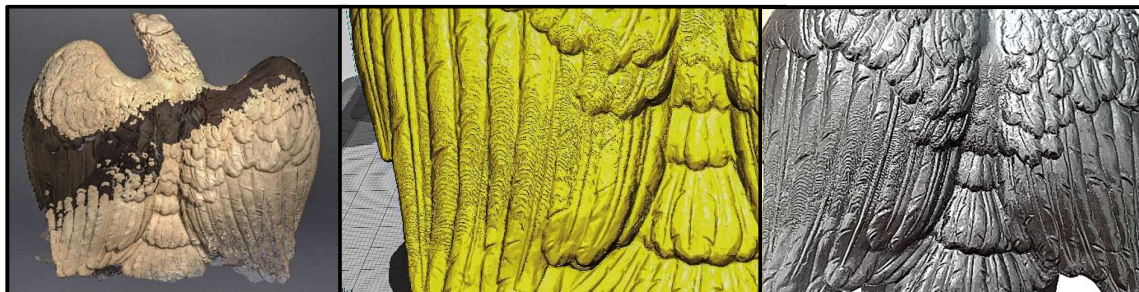

Figure 11: Gap in the point cloud (left), resulting visible structures of auto repair routines in slicer (middle) and printed object (right)

software mostly lacks efficient functions to add new points to an existing point cloud and the scan may have to be repeated in total.

Floating parts develop out of small point clouds which cannot be associated to the main object cloud. Sometimes they are caused by background points which have been caught in the scan. These parts are obsolete and must be removed. After meshing the digital object, the mostly automatic process will have created a surface model (STL-file) cured of many faults.

Figure 12: Floating parts in the point cloud of the eagle, "ExStar" meshing option

The semi-automatic process provides a welcome assistance to the modification process. The algorithm identifies "standard" faults and executes the repairs. Parameters of identification and repair limits can be set. It is up to the user to decide about their optimal setting.

After meshing the digital object is still an incomplete surface model and further improvements are required. The Autodesk "MeshMixer" is a freely available software providing a range of functions to improve model quality. The display will identify open areas by highlighting outside surfaces in white, inside surfaces in pink and rendering the edges in blue. Holes and gaps become clearly visible. The "Inspector" function will highlight all identified holes and offer an automatic "Hole fill" algorithm. The gaps and holes marked in red and magenta exceed the capabilities of the algorithm and must be cured manually.
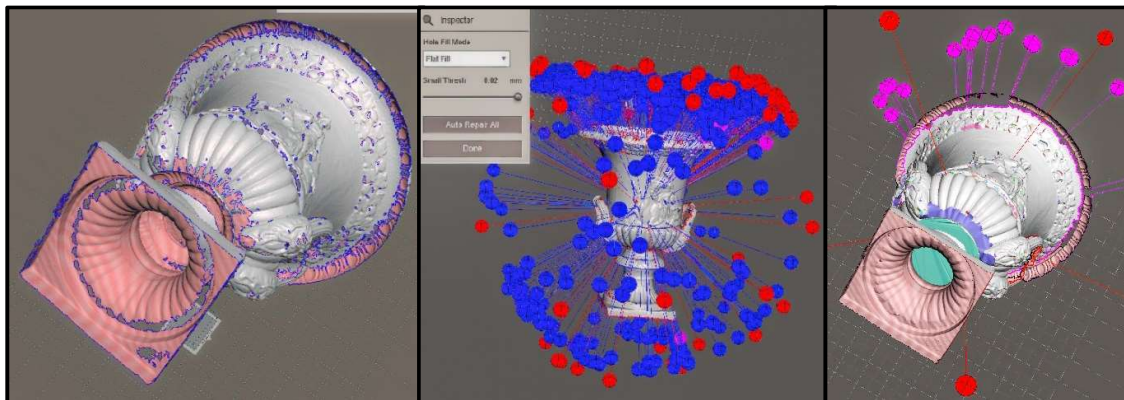

Figure 13: "MeshMixer" vase with gaps (left), "Inspector" mark up (middle), vase after automatic hole filling (right)

Although tempting, not all holes should be closed automatically. The historic original object (vase) will contain some cracks, gaps or bumps in the original structure which need to be kept and require careful manual modifications. Replication of the original geometry is the goal, not the perfectly approximated surface.

Figure 14: Manual modification of vase details representing the original (faulty) structure: (a) original vase, (b) meshed surface in "MeshMixer", (c) manually closed holes [12]

Smoothing the surface is part of the "ExStar" meshing routine. However only three differentiation possibilities in the parameter settings ("low, med, high") let us expect an unwanted change in the original geometry. "MeshMixer" offers a range of "sculpting" functions which will also be helpful to smooth specific areas manually. Additional smoothing was not applied to the eagle (Figure 11). Relying on the automatic hole closing routine has proven to be deceptive.

Adding analytically defined geometry is possible in "MeshMixer" by adding planes and filling the resulting voids with matter. The geometry of the base of "Benedicta's" bust is cubically shaped but has not been completely captured in the scan because the object was standing on a table.

Figure 15: Filled up base of "Benedicta" [14]

Alternatively, planes can be used to cut off surplus matter. In case of the bell a horizontal plane is added 5 mm above the lower edge in order to create a straight lower brim.

Figure 16: Bell mesh before cutting (left), bell with cutting plane in "GOM Inspect", bell after cutting base [14]

Replacing scanned elements by mirroring at a plane of symmetry was used to create the model of the chair. The rod structure of the chair made it extrelemy difficult to capture the single rods without scanning structural elements in the background at the same time.
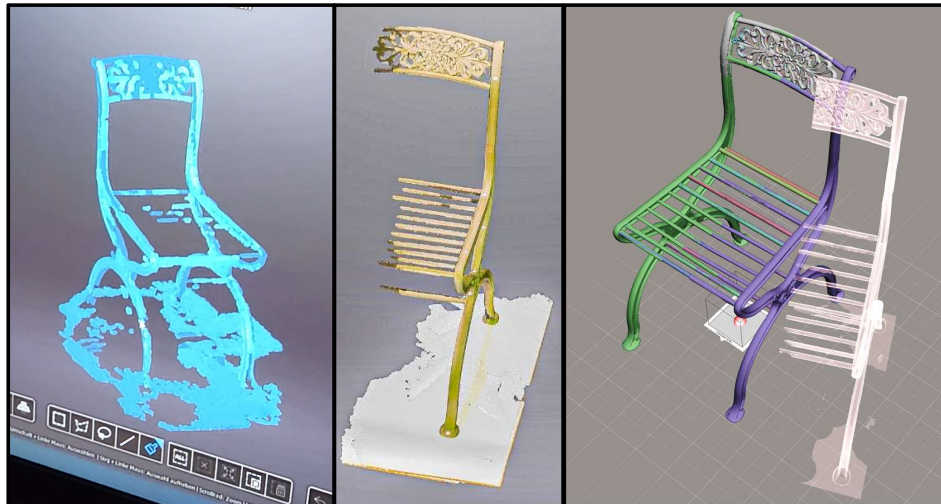

Figure 17: Incomplete preview, complete half (point cloud), joining mirrored halfs in "Mesh Mixer"

Replacing scanned elements by analytically modelled elements was used to cure problems with the bust of "Benedicta" and the vase. Both could have been repaired in "MeshMixer", however using analytically modelled elements was easier.

The scanner could not reach all the way into the inside cavity of the vase where a huge gap in the inside surface was left after meshing. The concerned area of the vase was at the inside diameter and therefore rotationally symmetrical. Analytically defined surfaces form the basis of modelling in CAD systems. Exporting the STL-file to "SolidWorks", sketching the inside onto the scanned contour and creating the new inside surface by using a "revolve base/boss" feature proved to be effective. However, the deviation from the original inside surface is significant.
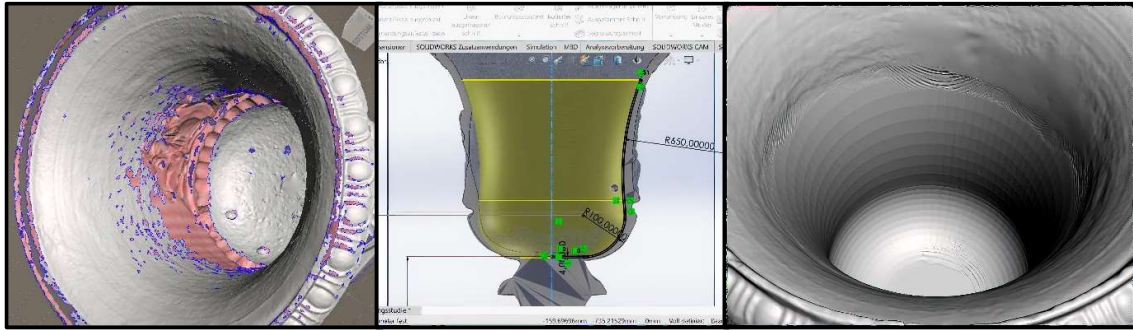
Figure 18: Inside after meshing (left), replacement sketch in "SolidWorks" [12] (middle), repaired inside surface [12] (right)

The bust of "Benedicta" features an inscription at the front of the base which proved to be difficult to scan by hand. The inscription was deleted in "MeshMixer", modelled in a "Fusion 360" and inserted into the model again.

Figure 19: Original inscription (top left), scanned inscription (top middle [14]), modelled inscription (top right [14]), base with deleted inscription (bottom left [14]), base with modelled inscription added (bottom right [14])

Aligning with horizontal plane and the **definition of the origin** by aligning the object with the world coordinate system are the last steps to complete the digital model. "GOM Inspect" provides effective functions to define the object´s origin by placing planes on the base surfaces, aligning straight lines with the edges and locating the origin at their intersection.
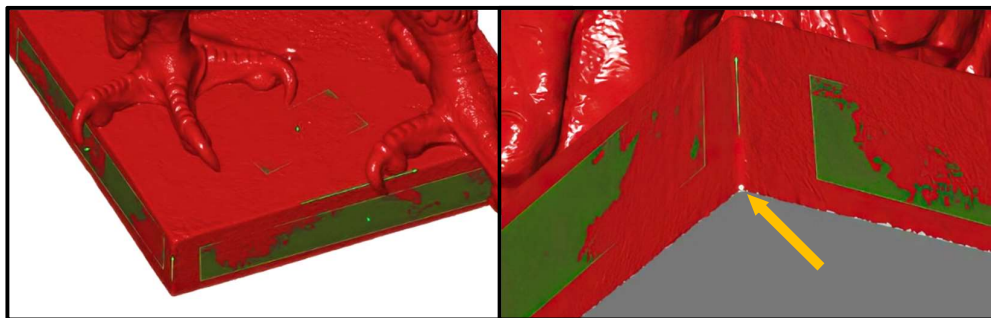

Figure 20: Base of the eagle with reference planes in green and object´s origin (yellow arrow) [11]

Aligning the object´s coordinate system with the world coordinate system is done by referencing the position with the grid display in "GOM Inspect":
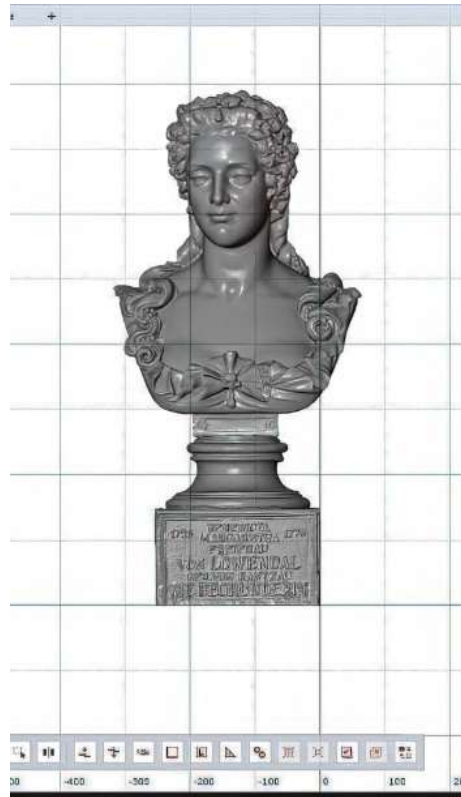

Figure 21: Aligning "Benedicta" with the world coordinate system [14]

Printing

Resin color options and surface quality led to the selection of stereolithography as printing process. Bell, eagle, "Benedicta" and chair were printed on a Stratasys NEO 450 printer. Size was scaled down to approximately 25%. Miniaturization was necessary due to the build space restrictions, but also reduces the level of details and consequently approximations loose significance.

Figure 22: Bell, eagle, "Benedicta" and Schinkel Chair printed on a Stratasys NEO 450

Summary

The process "scan – slice – print" starts with the selection of the appropriate soft- and hardware. Software selection must consider that specific model modification functionalities may be required which exceed the capabilities of the proprietary scanner control software. Research about available software, required additional capabilities and their specific application in the context of replicating historical (i.e. "damaged" objects) seems trivial but is extremely important.

Object size in this case required the use of handheld scanners which introduces the "human factor" into the process. The rough but otherwise monotonous surface of the bell allowed good manual capture by the scanner, however leading to multiple scans. Multiple scanning of the same surface area led to huge file sizes and long scanning times. The rod structure of the chair could not be fully captured manually and needed extensive manipulation of the model afterwards.

After scanning, necessary and optional modifications and the limitations of automatic routines have to be identified. A careful selection between automatic and manual processes is expedient as well as definition of parameter settings for all transformations (e.g. optimize setting of number of triangles for meshing). Slicing software selection was found to be no issue. The proprietary slicer-software of the printers was used which included all necessary functions. Although the digital model is completed before printing, the printing process will influence the data modification process and may be considered. The surface quality and the color range of the stereolithography-process proved to produce the highest quality prints and therefore demands a matching model quality. Printing at 25% size was advantageous.

Even if all parameters are set to the optimum values during the replication process, the digital model will only approximate the original object and a modelling process will always be more exact. Lack of original digital object data however limits any statement about the quality of the model to subjective statements.

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