PRESERVING HISTORICAL ARTIFACTS THROUGH DIGITIZATION AND INDIRECT RAPID TOOLING

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Abstract

This case study presents digitization and replication of a historical plaster pattern of Robert Morris, one of the founders of the United States of America. Details of the scanning stages and engineering solutions developed for successful digitization such as fabrication of a rotary table and its inductance to the scanning software are introduced. The three rapid prototyping technologies that produced resin, thermoplastic, and metal composite copies in this study are discussed in detail. Subsequently, the use of Room Temperature Vulcanization molds to cast polyurethane copies is demonstrated. A detailed comparison for the three rapid prototyping technologies as well as producing polyurethane copies is provided.

Background

The process of replicating historical artifacts is not new. With the development of 2-D computer scanning technologies, historians, librarians, archivists, museum curators, and amateur enthusiasts have been digitizing historical works such as books, records, documents, and making them available to the public [1]. In the past decade, the technology has greatly advanced from these 2-D computer scanners to 3-D digitizers. This technological advancement has broadened the users of reverse engineering to medical technologists, historians, anthropologists, paleontologists, primatologists, and forensic scientists. In this context, virtual reconstruction for forensic applications has been one of the growing application fields of reverse engineering, replacing the hard work of skull reconstructionists [2].

The virtual reconstruction process starts with digitization of physical elements such as bone fragments of a primate or a crime victim. These digitized elements are manipulated by eliminating noise, filling in missing geometric data, and assembling them within the CAD environment. The next step beyond the virtual reconstruction is to realize the CAD model via rapid prototyping. One of the other growing applications of the virtual reconstruction is the generation of custom implants or scaffolds for replacement of missing sections of human bones [3], which has relied on rapid prototyping and tooling in fabrication of these substitutes and implants.

Data acquisition from fragile historic artifacts residing in museums faced the following challenges during scanning of the objects [4]:

- The artifact could not be touched by hand or an instrument.
- The artifact could not be moved.
- The job would need to be accomplished during the normal museum hours due to very high after-hours security requirements.

This paper outlines the details of a study conducted at Robert Morris University to replicate the bust of the founding father after whom the university was named.

Case Study: Bust of Robert Morris

Robert Morris (1734–1806) was a Pennsylvania merchant who helped finance the American Revolutionary War. Morris signed the Declaration of Independence, served in the Continental Congress, and gave away his fortune to help fund the Colonial Army. During the war, he served as Superintendent of Finance, working to establish the first national bank and improve the emerging nation's credit. Morris later served as one of Pennsylvania's earliest senators [5].

This study presents a case on scanning and duplicating a pattern used in fabrication of Robert Morris statutes and busts for museums and parks. The pattern, shown in Figure 1, was restored at the Carnegie Museum of Art in Pittsburgh, Pennsylvania. In the summer of 2007, the Robert Morris University (RMU) Engineering Department was given the task of digitizing and duplicating the pattern without causing any damage to it. Because it was made from plaster and almost 100 years old, it had to be handled very carefully and could not be used as a molding master pattern. The pattern was scanned prior to restoration with the intention of rescanning after the completion of restoration. A sand mold was also originally planned to be fabricated through rapid manufacturing technologies for obtaining full-scale replicas to market or to give as gifts. For completing such an application, 3-D scan data should be highly accurate to avoid sacrificing any detail made by the artist.

Hardware and Software Technologies Used

For digitization, a Minolta Vivid 910 scanner and Geomagic Studio software were used. The camera could scan large free-form objects with a dimensional accuracy of 0.1270 mm. To assist in the scanning process, a Parker Automation 200 RT Series motor-driven rotary table with a diameter of 203.20 mm and a maximum load capacity of approximately 68 kg was available, but not used. Because of the geometric complexity of the bust, special attention had to be paid to cavities and shiny surfaces. Because the scanner did not have the flexibility to reach hard-to-access details, the scanning process became more tedious than originally expected.

Scanning Process

The main difficulty encountered during the scanning process was the special care requirement in handling a historical artifact with a value more than $100,000. The pattern would fit in a 0.9144 m × 0.9144 m × 0.9144 m work envelope and weighed approximately 27.22 kg. Such a large object with a vulnerable structure due to its fragile, aged body required that a special scanning platform be fabricated. Figure 2 shows the rotary table built to accommodate this large part in a stable manner. Even though the original rotary table can handle up to approximately 68 kg, its footprint was not large enough for the pattern [6].

Once placed on the platform, the object would not be moved. Because the original platform spins automatically to enable data capture through 360º during the scanning process, it was necessary that the manual platform rotate as well. The investigators calibrated the new rotary table as if it was the one connected to the PC with the Geomagic Studio software and accomplished each shot by matching the angle of rotation at the software tool and the manually driven table. Various rotation angles were used. After a brief study, a rotation interval of 30º was selected as the stepping angle for the consecutive scans. As the Geomagic software was instructed to rotate the original rotary table 30º for the next scan, the investigators manually moved the second table with the actual piece 30º.

The captured data were processed within the Geomagic Studio reverse engineering software. This handling process consisted of three phases: point, polygon, and shape. The following functions were utilized during the data manipulation stage:

- Point Phase (filtering points, registration, reducing noise, filling holes, and merge)
- Polygon Phase (cleaning, filling holes, boundary editing, relaxing boundary, defeature, decimating polygons, sandpaper, relaxing polygons, sharpening wizard, and manifold operation)
- Shape Phase (saving the file in STL format)

Figure 1. Historical Pattern of Robert Morris after Restoration

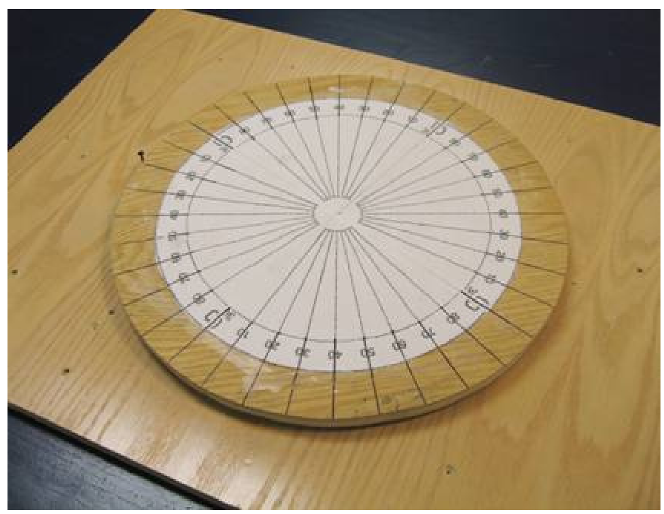

Figure 2. Custom Rotary Table Made to Scan the Robert Morris Bust

The most tedious data handling steps were registering individually scanned surfaces and cleaning up spikes and inaccurate areas due to the size and complexity of the scanned object. Upon completion of the reverse engineering process, the file was saved in STL (Stereolithography) format, which is a triangular-based image of an object's 3-D surface geometry. The STL file size was approximately 200 MB. The polygon model of the pattern and the STL file resulting from the polygon model are presented Figures 3 and 4, respectively.

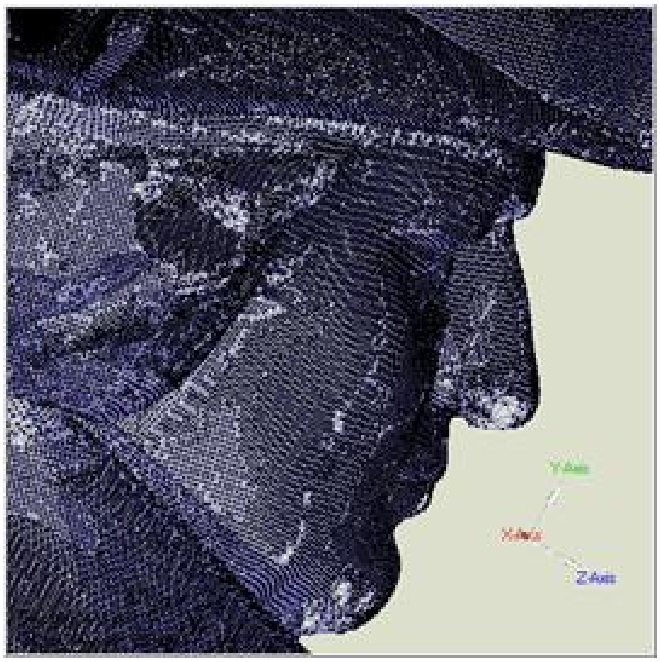

Figure 3. Results of the Scanning – the Polygon Model

The STL file was later used to create 3-D physical replicas of the original piece. Replicas were produced employing the following equipment: (i) 3D Systems Viper Si Stereolithography (SLA) machine, (ii) Stratasys Dimension Elite Fused Deposition Modeling (FDM) machine, and (iii) EX ONE ProMetal RXD (R1) 3-D Metal Printing machine, all housed in the RMU Engineering Department.

Prototyping of the Bust

The Viper SLA failed to build the part initially due to PC hardware failure at the machine. It was later realized that the Viper SLA's controller unit had to be upgraded to process such a large STL model. The number of triangles had to be reduced to control the STL file size for handling without losing the details or accuracy of the data as well. The hardware upgrades helped improve the physical capabilities of the SLA system and resolved the main issue before the prototyping stage. The DSM-Somos WaterShed 11120 clear SLA resin was used to produce the scaled Robert Morris bust shown in Figure 5. Next, the Dimension Elite FDM machine produced the bust with the same scale using ABS plastic without any problems. However, employing ProMetal's RXD (R1) was not possible due to its small build envelope. Consequently, The EX ONE Company helped RMU build the replica by using an R2 machine that had adequate build volume. Thirty micron 420 stainless steel (S4) powder was used to fabricate the metal replica. After the build process, the piece was infiltrated with bronze to make it durable enough for handling. Both the FDM- and ProMetal-built parts are presented in Figure 6.

Figure 4. The STL File

Figure 5. SLA Part Made with DSM-SOMOS Watershed 11120

Figure 6. ABS and S4/Bronze Reproductions Made with FDM (left) and ProMetal 3D Printing (right) Technologies

Indirect Rapid Tooling Project

Indirect rapid tooling can be realized by utilization of various processes including Room Temperature Vulcanization (RTV) based on silicon rubber molding. Employing a metal composite pattern, the authors fabricated tin-cured silicon rubber molds to cast polyurethane replicas of the RP pattern.

The RP pattern was built in the ProMetal's R2 machine using a stainless steel (S4) base with bronze infiltration, as seen in Figure 6. A two-piece silicone rubber mold was built around the pattern. The molding material selected was SMOOTH-ON's Moldmax 40 (40A tin silicone) [7]. Approximately 20 hours was deemed suitable for curing time to obtain a solid mold. However, the molding was held longer to ensure complete curing. Moldmax 40 was ideal for transferring the details of the RP pattern. It also carried the characteristics of other advanced silicone molding materials: (i) good release properties and mold life for casting polyurethane, (ii) low shrinkage and good dimensional stability, (iii) good tear resistance, (iv) high elongation for easy removal of complex parts, and (v) medium mixed viscosity and medium hardness.

The material selected for the RTV process was the fast setting Smooth Cast 320, which is a polyurethane material, also from SMOOTH-ON. It sets in about 10–15 minutes and works well with the selected mold material [8]. Mann Technologies 200 Easy Release Agent was also employed in the process. The mold halves and a polyurethane replica produced by them are presented in Figure 7, and a finished and painted replica is presented in Figure 8.

Table 1 illustrates the dimensional accuracy of the processes used including ProMetal, SLA, FDM, and RTV Silicon Rubber Molding, fabrication lead times and costs for making a single Robert Morris bust replica. The cost of making an RTV mold, the cost of the ProMetal R2 piece, and the lead time for the ProMetal process are given in the table as well. The following details were taken into account while constructing Table 1:

- The fabrication lead times include post-processing times for each process.
- The part and molding cost for the RTV process include the material cost and the labor involved.
- For the RP processes, there can be two types of cost estimation: (i) rough quote based on the weight of the RP part, and (ii) precision quote based on the build time [9]. The precision quote considers the cost elements incurred during three stages: pre-process, process, and post-process. These stages include CAD design, file preparation for RP hardware, set up of the RP hardware, cleaning and finishing processes, post-curing, taxes, and profits.
    - The Robert Morris pattern fits in an envelope of (x-axis) 117.60 mm x (y-axis) 102.10 mm x (z-axis) 91.70 mm. Its volume was calculated as 2.2780 x 10^5 mm^3 by the 3D Systems SLA Viper software, and 2.2696 x 10^5 mm^3 by the Stratasys' FDM/Dimension machine. The material cost for the SLA Viper System was $61.23, and the material cost for the FDM/Dimension was $60.96.
    - While the FDM/Dimension machine costs $20/hr for use, the same cost factor for the SLA viper is $47.29/hr. ProMetal R2 operational cost is not known precisely but can be estimated to be within the $20 to $30 range.

Based on the information supplied in Table 1, it can be concluded that producing the part via FDM Dimension incurs the least cost compared with the other two RP processes.

However, the SLA process is the fastest and delivers the best accuracy of the three technologies. Nevertheless, these RP technologies are still not cost effective for directly replicating artifacts with a relatively large part envelope, even after scaling down dimensions of the pieces. For instance, for a batch of 50 SLA-made busts, the cost will still be $387/piece. Moreover, all three RP technologies require long build times and therefore cannot be relied upon for increasing productivity even with smaller batches.

Table 1. Comparison of Prospective Replica Materials and Associated Processes

Material/ Process	S4/ ProMetal	Somos 11120/ SLA	ABS/ FDM	PU/ RTV
Mold Cost ($)	-	-	-	1,547
Dim. Accuracy	± 0.127 mm and ±0.2% for shrinkage	**Varies between ± 0.0508 mm - ± 0.2540 mm [10]	± 0.2540 mm [11]	0.1016 mm/mm for shrinkage
Lead Time (hr)	*53	14.50	19.02	*** 24.20/ 0.20
Part Cost ($)	1,500	652 [12]	408 [13]	1,560

*Lead time includes debinding of the binder and the infiltration of bronze. Post processes may take up to three times of the actual RP process time. Shot blasting may also be used in improving surfaces.
** Horizontal and vertical accuracy, and accuracy for the first vertical inch and afterward, are included.
*** RTV mold fabrication lead time and molding lead time are presented.

Figure 7. A Polyurethane Replica and Its Silicon Rubber Mold Halves

In this study, the ProMetal R2 model was utilized as a pattern in making the RTV molds. This adds to the cost of the RTV molding process, and the resulting replica is the most expensive with a cost of $1,560. However, this figure is only for one part. Because the mold can be used for a batch of 50 parts, this cost can be reduced to approximately $44/piece. Similar results can be obtained for SLA/RTV molding or FDM/RTV molding couplings. Because SLA delivers the best dimensional accuracy, surface finish, and is second best in cost, it can be used with the RTV process for making replicas. SLA/RTV coupling results in a cost of approximately $27/piece for a batch of 50 parts. In the case of the RTV molding, close to 50 pieces can be made in an eight-hour shift once an RTV mold is built. Two molds will produce twice as many, though a batch this size will take a substantially longer time to build directly with the RP systems used in this study. However, the only drawback of the RTV molding process is having less dimensional accuracy compared with the replicas made directly at the RP systems.

Figure 8. Finished Robert Morris Bust Replica with an Added Base

Conclusions and Future Work

One of the most promising uses of reverse engineering technology is heritage conservation. Reverse engineering and rapid prototyping can be employed in preserving history. This study is an account of efforts made to preserve an important artifact at Robert Morris University. Even though it was a non-conventional project for the investigators due to its sensitive nature, various engineering problem-solving methods were applied in the scanning and replication processes. In the near future, the investigators plan to employ the capabilities of the RMU Engineering laboratories to work on collaborative efforts with forensics scientists or anthropologists. There is an ongoing development effort to include some of these subjects within the ENGR 4801 - Reverse Engineering and Rapid Prototyping course curriculum.

The digitized data resulting from the reverse engineering process could be used in preparation of digital and interactive exhibits and bringing these artifacts to many more people through Web resources. By helping the preservation process, the engineering field will have a great role in preserving our past. By also creating such incredibly detailed and identical replicas of historical artifacts, we can ensure that the artifacts will never be lost.

In terms of the indirect tooling applications, an RP/RTV molding combination seems to be the logical answer for making replicas of historical busts at this dimensional scale. Once an RTV mold is fabricated, replicas can be made about one every 10–15 minutes at a fraction of the cost of RP processing methods. The only drawback of such a system is again the tool life. It is very limited, and may require replacement after only 50 pieces. Additional manufacturing volume requirements make use of a set of molds necessary, also adding to the overall cost. However, in this case study, the authors showed that making a limited number of replicas, perhaps 50 to 100, is justifiable in terms of the costs and the quality obtained through the process.

Future work by the authors will include: (i) influence of part dimensional requirements (scale) on process selection for rapid manufacturing, and (ii) effect of manufacturing volume requirements on process selection for rapid manufacturing. Future work may also involve rapid-tooling approaches other than RTV molding including sand casting or injection molding.

References

[1] R. Rosenzweig, "Digital History: A Guide to Gathering, Preserving, and Presenting the Past on the Web." Philadelphia, PA. University of Pennsylvania Press. 2005.

[2] American Academy of Forensics Sciences, Resources, http://www.aafs.org/default.asp?section_id=resources&page_id=choosing_a_career, retrieved December 1, 2008.

[3] D. Zollikofer, "Virtual Reconstruction: A Primer in Computer-Assisted Paleontology and Biomedicine." Hoboken, NJ. John Wiley and Sons. 2005.

[4] Leica-Geosystems, Project Brief http://www.leica-geosystems.com/corporate/en/ndef/lgs_64189.htm, retrieved December 1, 2008.

[5] Robert Morris University, History and Heritage, http://www.rmu.edu/public-relations-and-marketing/content/history-and heritage.aspx?it=&ivisitor= , retrieved December 1, 2008.

[6] A. Sirinterlikci, O. Uslu, and Z. Czajkiewicz, "Replicating Historical Artifacts: Robert Morris Case Study." SME 3D Scanning Conference, Lake Buena Vista, FL. May, 2008.

[7] Smodev, Mold Max Series, http://tb.smodev.com/tb/uploads/Mold_Max_Series_TB.pdf, retrieved December 1, 2008.

[8] Smooth-On, Smooth Cast 320, http://www.smooth-on.com/index.php?cPath=1210, retrieved December 1, 2008.

[9] L. Ding, "Price Quotation Methodology for Stereolithography Parts Based on STL Model," *Computers and Industrial Engineering,* 52, 2007, pp. 241–256.

[10] R. Noorani, "Rapid Prototyping: Principles and Application." Hoboken, NJ. John Wiley. 2006.

[11] T. Grimm, "3D Printer Dimensional Accuracy Benchmark," *Time Comprehension Technologies*, September/October 2005, p. 1–4.

[12] Kellyniamsla, Calculator, http://www.kelyniamsla.com/calculator.php, retrieved December 1, 2008.

[13] Fdmonly, Cost Estimator, http://fdmonly.com/estimator.asp, retrieved December 1, 2008.

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