https://doi.org/10.2352/issn.2168-3204.2018.1.0.33

From the Inside Out: Practical Application of 3D Imaging Techniques in Art Conservation

Scott Geffert, Daniel Hausdorf, Joseph Coscia, Oi-cheong Lee, Dahee Han, Wilson Santiago, Frederick Sager, Matthew Cumbie, and Christina Hagelskamp, The Metropolitan Museum of Art, New York

Abstract

One of the centerpieces of Chinese sculpture in the Asian Art collection at The Metropolitan Museum of Art is an early seventh-century seated Buddha (19.186). The life-size image was executed in jiā zhù 夾紵, or dry lacquer, a technique of layering woven textile saturated with Asian lacquer to model hollow three-dimensional objects. From 2016-2017, The Met's Buddha was examined and treated in the Department of Objects Conservation in preparation for the exhibition "Secrets of the Lacquer Buddha" at the Freer | Sackler Galleries in Washington, D.C. (December 9, 2017 to June 10, 2018). The exhibition brought together for the first time the only three known sixth- and seventh-century, life-size Chinese lacquer Buddha sculptures from The Metropolitan Museum, the Walters Art Museum in Baltimore, and the Freer Gallery of Art. Working in close collaboration, Met conservators, mount makers, and members of the Imaging Department designed an elaborate carbon fiber internal support for the Buddha, using state-of-the-art 3D scanning and milling technologies to safeguard this delicate work during transport and display. This paper documents the entire project from initial imaging to the successful fabrication of the required support structure.

Figure 1 Buddha, Probably Amitabha (Amituofo), Early 7th century, Medium: Hollow dry lacquer with traces of gilt and polychrome pigment and gilding, Accession Number 19.186.The Metropolitan Museum of Art

The Project

Acquired by The Metropolitan Museum in 1919, the request from the Freer | Sackler Galleries to borrow the Buddha provided an opportunity for its renewed study, documentation, and conservation. Traditionally, Chinese dry lacquer figural sculptures were constructed by layering and sculpting strips of cloth soaked with a mixture of lacquer and other materials—such as burned bone—onto a clay core. For stability, the Met's Buddha has pieces of wood integrated into the bottom edge, the back of the head, and, in the back of the sculpture, like a spine. The eyes are of leaded glass and embedded metal wire is supporting the elongated earlobes. After the lacquer shell was formed, the clay core was removed, leaving a light-weight but rigid shell that was then painted and gilded.

Considering its age, this life-sized hollow lacquer sculpture is in remarkable condition overall, though some of its components, including its halo and hands are now lost. However, a thorough examination revealed a delaminating matrix, lifting gold foil and friable paint layers, as well as multiple repairs that were identified using X-ray radiography. Fine cracks in the lower body and the legs weakened the structure causing a slight sagging of the Buddha's lap when positioned upright. In addition, the bottom edge of the figure proved more fragile and unstable than anticipated. These structural issues prompted the idea of an internal support to reduce internal stress due to the sculpture's own weight, and to prevent further abrasion to the fragile bottom edge. A successful mount would also support the object, reducing the inevitable risks that occur during transport.

Support mounts are commonly used in museums to allow for appropriate and safe display of objects; The Met employs a team of five full-time conservation preparators to create custom designs, primarily using brass. We anticipated that the fabrication of such a mount for the Buddha would require substantial handling to take measurements and to fit individual elements—our conservators hoped to reduce this kind of handling. A traditional brass mount would have required a complicated multipart, jointed framework with the potential to fail during transportation. Furthermore, a mount made entirely of brass would be unsuitably heavy for a light-weight sculpture made of cloth and lacquer. For these reasons, the mount for the Buddha needed to be made with a light-weight but rigid material. And to accomplish this fabrication, we identified 3D printing, CNC milling, and molding as promising methods to achieve our goal. With this in mind, Ronald Street, Senior Manager, 3D Image, Molding, and Prototyping, was approached to contribute to this project and share his extensive expertise in 3D imaging and high precision reproductions. Tragically, The Met suffered a great professional and personal loss when Ron passed away in November 2016, after which the Museum's Advanced Imaging Team picked up where he left off.

The Advanced Imaging Initiative

The Metropolitan Museum's Advanced Imaging Initiative began as a natural evolution of the Photograph Studio, which has been in continuous operation since 1906. The department was rebranded as the Imaging Department in 2015. The initial goal of forming the Advanced Imaging Initiative was to consolidate imaging experience and activity to one department. Ron Street, an early pioneer of 3D imaging for cultural heritage, had worked in the Museum's Merchandising Department since the 1980s. His core skills and activities were related to creating artwork reproductions, but over time his expertise was regularly extended to the Museum's art conservation departments. When the Advanced Imaging initiative was created, Ron was brought onto the team, thus successfully and effectively consolidating 2D and 3D imaging expertise. Now working within the Imaging Department, Ron was able to share his knowledge with members of our post-production team. The primary focus of our advanced imaging efforts is to explore the practical application of laser scanning and photogrammetry. Our secondary focus is the overall integration and standardization of all technical imaging methods. Ron's tireless dedication to sharing his knowledge allowed our team to forge ahead with zeal and enthusiasm.

Interior Test Capture

In an initial meeting, the conservators expressed to the Imaging team that their primary goal was to achieve detailed and accurate photographic documentation allowing them to monitor precisely the Buddha's condition. In general, high resolution photographs are used to map condition issues on works of art, document conservation treatments, or, in this case, to document the condition of this fragile and important Buddha prior to going on loan.

In addition to high resolution photography, the team hoped to capture the sculpture's condition in 3D to document any dimensional changes that might occur during treatment or as a result of transit, as well as to determine the original position of the sculpture. Another benefit of a 3D capture was the creation of a physical model that would be a critical tool for the design of the mount, allowing the conservators to create the mount precisely and indirectly, significantly reducing the amount of handling the actual sculpture.

It was immediately clear that we could image the exterior of the Buddha using photogrammetry and laser scanning, however, capturing the internal recesses of the sculpture would prove to be significantly more challenging. Laser scanning and photogrammetry using a DSLR camera or even a compact mirrorless camera could, at best, only capture a small portion of the interior, so we needed to explore another approach to image the narrow and complicated interior. A past experience with scanning the interior of a bell-shaped object using Agisoft PhotoScan Pro to extract camera locations led us to experiment with this software for the Buddha. We ran a test using an iPhone, which was useful because of its diminutive form factor, exceptional camera, and close-focus capability.

Using an iPhone 6S Plus and 1Westcott Flex Bi-Color LED Mat (1 x 1 ft.) fixed to a ball head on a support rod, we captured an array of overlapped images. With the sculpture in its natural seated position, it was physically challenging to work below the piece while taking care not to touch the surface, but using a remote control app on a second phone allowed us to compose and preview each capture. The images were run through Agisoft PhotoScan Pro, a professional tool for photogrammetry, and, without the need for any special configurations, the resulting model and texture were successfully rendered, fulfilling all expectations. (Figure 2)

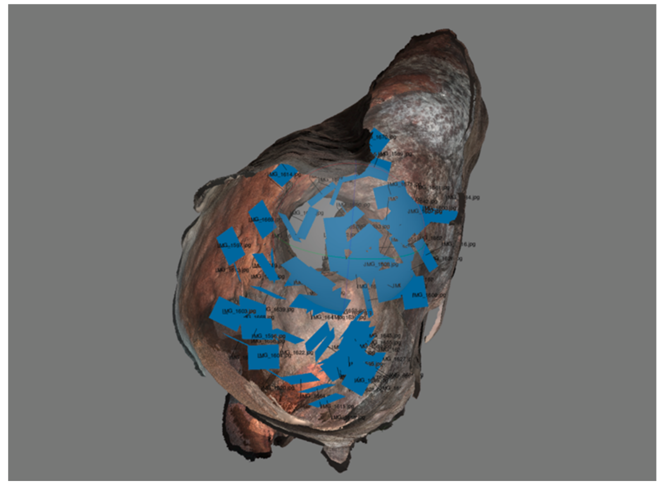

Figure 2 Screen capture of Agisoft Photoscan interior 3D rendering and initial iPhone test camera positions

Developing and Implementing a Digitization Game Plan

With the experience gained from our successful test we focussed on developing an efficient capture strategy. The Buddha was placed on its back using a stable support engineered to allow the sculpture to be moved safely from a vertical to a horizontal position. In this position, safe and unobstructed access to the hollow interior was established to facilitate digitization.

The digitization began with laser scanning of the exterior using the FARO® Edge HD arm, operated by photographers Joseph Coscia and Oi-Cheong Lee, working in close collaboration with the Advanced Imaging team. We often start with laser scanning to establish a baseline, as it is the most precise measurement device in our equipment pool. The exterior of the artwork was digitized, including the base. On the interior, we scanned as much of the surface as we could access with the scanning device. It was important to capture as many of the interior edges as possible because these areas would later be the critical keys to registering the laser scan data with additional 3D data sets derived from photogrammetry. (Figure 3)

Figure 3 Photographers Oi-Cheong Lee, and Joseph Coscia Jr. operating the Faro HD Laser Scanner

Once laser scanning was complete, we continued to image the Buddha's interior using photogrammetry. The photographers managed the iPhone camera and light positioning while the Advanced Imaging team concentrated on focusing and capturing using the iOS App Camera Plus Pro. Due to the complex geometry of the interior and limited access, the flexlight being used during the operation resulted in an unilluminated area above the iPhone. (Figure 4)

Figure 4 Scott Geffert remotely focusing and triggering the iPhone positioned by Joseph Coscia Jr. and Oi-Cheong Lee deep inside the interior cavity of the Buddha. Advanced Imaging team member Dahee Han observes.

Figure 5 Scene-referred camera calibrations in preparation for a photogrammetric capture session to image the entire outside of the artwork

To provide more control, the illumination was supplemented with 4 Citizen CL 100 High CRI LEDs mounted to custom heat sinks driven by an eldoLED POWERdrive 180D equipped with a dimmer wheel to adjust power output. Having the ability to control and shape the light pattern was crucial to the success of the imaging. On several occasions, the photographers had to remove the camera rig to adjust the lighting especially when imaging the deep cavities of the arms and neck. After the interior imaging was completed, the artwork was returned to its vertical position, and areas that couldn't be reached while horizontal were digitized to complete the imaging session.

With the first round of imaging complete, the Buddha was placed onto a PhotoRobot Turntable System in preparation for a 360° sequence for photogrammetry that progressively reduces the number of captures in the range from 0 to 90° (e.g. 72°, 36°, 18°, 9°, 6°, 3°) in an effort to improve efficiency and to reduce overall light exposure. Taking the time to capture photogrammetry in addition to full laser scanning is critical to properly evaluate the quality of our photogrammetry; there is no better benchmark for metrology than a laser scan. The photogrammetry process captures a set of 50 megapixel ISO 19264 validated scene-referred images that can also be useful as a complete photographic documentation of the exterior. (figure 5)

Data Processing

When a photogrammetric model is generated from an image set, the quality (visible in the level of visible surface detail) is typically less than that of a laser scan. By aligning the photogrammetrically-generated mesh with the laser scan mesh data, it is possible to remove the photogrammetry mesh and remap the high resolution images onto the laser scan generated mesh, thus improving the quality of the data overall. At first glance, our approach may appear to have many redundancies, but we have found that each data set we create helps to build our knowledge base and defines gaps in our program as well as our best practices. When evaluating new hardware and software, we often repurpose capture data sets for comparative analysis.

We used Agisoft PhotoScan Pro to generate the photogrammetry data. With the iPhone imaging set, we built a textured model of the Buddha's interior. In this project, it was important to create an accurate interior photogrammetry mesh to fit into the laser scan data. Referring to photogrammetry calibration scale bars included in the scene, we measured the model to 1 mm accuracy. (figure 6)

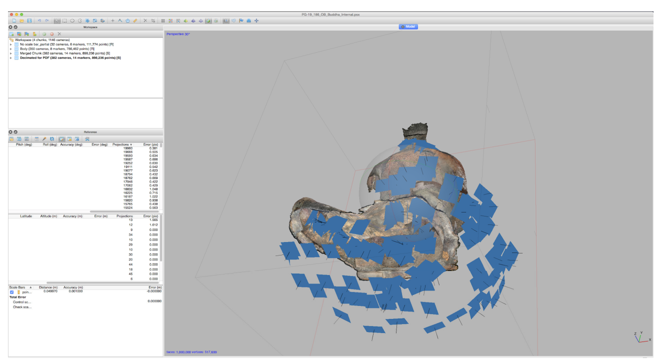

Figure 6 Screen capture of Agisoft Photoscan showing final camera positions and the 3D rendition of the interior form

The exterior 360° capture set was also processed in PhotoScan Pro. After the photogrammetry models were generated, we started assembling the data in Geomagic® Control X™. We then imported the laser scan and interior iPhone photogrammetry meshes into the software, aligning them with the Best-Fit alignment tool. Since we precisely scaled the interior photogrammetry mesh, aligning the laser scan mesh to the iPhone photogrammetry mesh was successful. (Figure 7)

Figure 7 Final exterior 3D model and surface texture, Final interior merged 3D model (laser scan / photogrammetry) and interior surface texture

Considerations for Mount Making - Materials and Methods

The fabrication of an internal support for safe display and transport of the sculpture was a primary goal of this project. The limited access to the Buddha's interior coupled with the irregular geometry required the mount to be made of multiple parts that could be securely assembled within the sculpture's cavity. The choice of materials for mount making in museums is limited since all materials must be tested to determine if they are safe to use in close proximity to or in direct contact with art objects. Although materials may provide sufficient structural support, they may emit trace amounts of chemicals that can harm art objects over time. Based on material tests performed at the Museum, two methods were considered: molding the mount from carbon fiber fabric and epoxy resin or 3D printing using nylon filament.

3D printing was a promising solution, but it soon became clear that this approach would not be feasible for this project. Not only did the Buddha's interior shape require an intricate multi-part mount, but the components also needed to be light-weight, rigid, and stable. In addition, not all of the mount components required the same stiffness or strength. Even further, some parts required perforations to allow for air circulation, thus preventing a potentially harmful microclimate to develop between the mount and the interior surface of the Buddha. Based on the experience from other 3D printing projects, we learned quickly that multiple test prints and fittings would be necessary to ensure that the parts meet the requirements and fit together perfectly. Every completed 3D print is final, which means that any modification of the design requires reprinting the part from scratch. Our testing revealed that this method would have been prohibitively expensive, especially since the museum did not own a 3D printer that could produce parts of the size needed for the Buddha's mount.

Molding the mount from layers of carbon fiber fabric laminated with conservation-approved epoxy resin proved to be a more suitable method. Carbon fiber has been used with great success on a number of recent Objects Conservation Department projects. In addition, this method allowed for customization during the fabrication. For example, parts could be structurally reinforced where required, or made lighter by using different weights carbon fiber cloth, or numbers of laminations. Carbon fiber reinforced epoxy resin is also easily workable. It can be cut, sanded, drilled, and glued allowing for further customization of the mount design during the fabrication process.

Molding the Mount from Carbon Fiber and Epoxy Resin

Due to the skill and experience of The Met's photographers and Advanced Imaging team, the resulting 3D model of the Buddha's interior was very accurate. An accurate geometry was absolutely important for the fabrication of a physical model of the Buddha's interior surface, which was milled from a block of high density polyurethane foam using CNC machining.

Using the compiled and aligned photogrammetry and laser scan data, a model of the interior cavity was inverted and edited using Geomagic Wrap®. At over 18 million triangles, the model was highly featured. Normally, a model with so much detail is desirable, but for the purposes of milling, the model was simplified while still retaining accurate dimensions. Deep undercuts would be problematic when reconstructing the milled pieces inside of the sculpture, so they were eliminated in the virtual model while still retaining important boundaries which would help support the sculpture. Holes and gaps were carefully filled following the curves and features of the surrounding surfaces. In addition, the 3D model was offset by 2.5 mm to account for a layer of acrylic felt that would be applied to the mount to provide some cushioning.

For the milling of the mold, the Museum collaborated with Digital Atelier, based in Mercerville, New Jersey, who specializes in laser-scanning and CNC-milling technologies. The company used their software to determine how many individual mold sections would be necessary to avoid undercuts during the milling process, while also ensuring that all carbon fiber parts could be withdrawn from the mold sections without getting stuck in undercuts. To create a usable mold, the high density polyurethane foam block was divided into 10 mold sections, aligned and keyed with carbon fiber pegs. (figure 8)

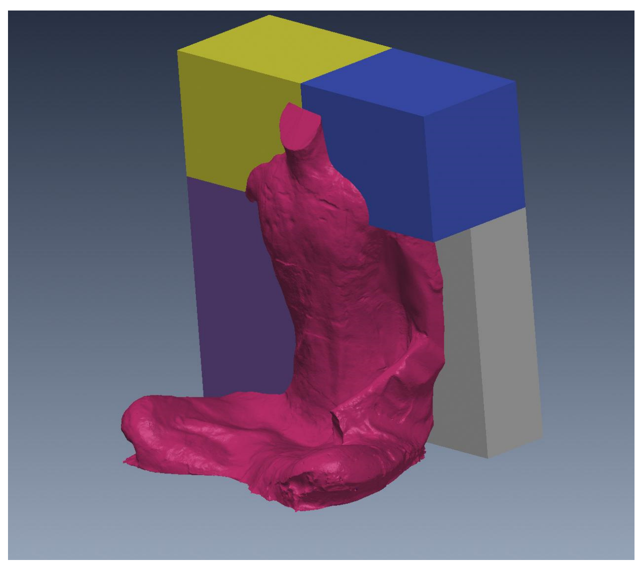

Figure 8 Partial view of inverted model and mold sections generated in preparation for CNC milling

After the milling was completed, the mold sections were primed for the molding process with two layers of epoxy resin.[1] A layer of wax[2] was then applied to all surfaces, to act as a release agent. Each component of the mount was molded by layering various carbon fiber cloths impregnated with the same epoxy resin. While thinner, plain weave patterns were used for the outer layers, the core was made of several layers of heavier carbon fiber cloth to provide increased structural support and rigidity.[3] (figure 9)

Figure 9 View of carbon fiber support elements in CNC milled molds

After de-molding, the edges of the mount components were ground and shaped so they could be test fitted in the Buddha's interior. A pattern of holes was drilled into each mount component to allow for air circulation. Then, an acrylic felt layer was applied on each mount component and all pieces were test fitted again. Most of the mount components aligned perfectly with the Buddha's interior surfaces, and only a few pieces required some custom fitting.

All mount sections were then connected using carefully shaped brass plates screwed onto weld nuts, which were fixed to the surface with epoxy resin. The next day, a multi-layered patch of carbon fiber cloth with epoxy resin was applied to reinforce the connection between each weld nut and the mount components. Once the weld nuts were fixed in place, all mount components were assembled inside the Buddha using the brass plates and wing bolts, resulting in a rigid and self-supporting carbon fiber construction.

The lower portions of the mount were designed and built stronger as they carry the weight of the Buddha. Eight large brass angles were anchored to these components using the same method described above. The angles connect the mount to a flat board, such as a piece of thick plywood to be used during transport, or to a pedestal for display. Due to the perfect confirmation between the carbon fiber shell and the inside of the Buddha, the sculpture is now held securely and cannot not distort in any direction. At the same time, the construction of the mount and the layer of acrylic felt allow for some flexibility and vibration dampening. The Buddha is now slightly raised, which alleviates the pressure on the fragile bottom edges as they do not touch the ground anymore. (figure 10)

The new mounting system makes it possible to safely transport the Buddha without any additional bracing or padding inside the crate, which could potentially damage the fragile painted and gilded surfaces. Only a collar from carbon fiber was made to further secure the head and neck of the sculpture. The Buddha was successfully transported to Washington, D.C. and installed at The Freer Gallery where it is on view until June 10, 2018.

Figure 10 View of final carbon fiber interior support

Conclusion

This project could not have been accomplished without teamwork and the specific expertise of everyone involved: the imaging team planned and captured the sculpture's form, the CNC milling was expertly accomplished by an outside vendor, and members of Objects Conservation deftly devised and crafted the final mount. The collegial collaboration between all of these groups allowed the project to move smoothly forward to successful completion. This project underscores the fact that cutting edge technology can perfectly coexist with time tested traditional expertise.

With the success of this project, we have continued to explore 3D imaging of small objects and interior spaces. We have tested a number of solutions from the dental and medical communities to explore miniature cameras and intraoral 3D imaging tools. In the meantime, the iPhone camera remains a viable and accessible option for others to explore as a supplement to other imaging tools. Our Advanced Imaging team has come a long way since its inception. The Buddha project is now completed, but to our team it underscores the value of centralizing imaging resources and developing best practices in the cultural heritage community.

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[1] [1] WESTSystem 105

[2] [2] Microcrystalline Wax

[3] [3] 3K, Plain Weave Carbon Fiber Fabric and 12K, Twill Weave Carbon Fiber Fabric, Fibre Glast Developments Corporation

Author Biographies

Scott Geffert is the General Manager for Advanced Imaging in the Imaging Department at The Metropolitan Museum of Art. His responsibilities include developing standards and best practices as 2D, 3D and computational imaging techniques continue to converge.

Daniel Hausdorf is an Associate Conservator in the Department of Objects Conservation at The Metropolitan Museum of Art. His responsibilities include the technical examination and treatment of wooden artifacts in the Department of Asian Art.

Christina Hagelskamp, Associate Conservator in the Department of Objects Conservation, is responsible for the technical examination and treatment of Asian lacquer objects at The Metropolitan Museum of Art.

Joseph Coscia Jr is the Chief Photographer in the Imaging Department at The Metropolitan Museum of Art. His responsibilities include guiding the museums team of 13 full-time as well as part time photographers.

Oi-Cheong Lee is the Associate Chief Photographer in the Imaging Department at The Metropolitan Museum of Art. His responsibilities include coordinating the museums team of full-time and part time photographers.

Wilson Santiago is the Imaging Production Manager in the Imaging Department at The Metropolitan Museum of Art. His responsibilities include refinement of 3D imaging techniques.

Dahee Han is an Imaging Production Assistant in the Imaging Department at The Metropolitan Museum of Art. Her responsibilities include 3D data processing and analysis.

Frederick Sager is the Supervising Conservation Preparator in the Department of Objects Conservation at The Metropolitan Museum of Art. His responsibilities include mount making, art installation, and the supervision of a four-person team.

Matthew Cumbie, Conservation Preparator in the Department of Objects Conservation at The Metropolitan Museum of Art, is creating mounts and installing art for all of the Museum's 17 curatorial department.

Acknowledgments

The authors would like to thank Carolyn Riccardelli and Marijn Manuels for proofreading the article.

https://www.metmuseum.org/blogs/collection-insights