Vol. 1, No. 2 ◆ Autumn 2006

The Journal of the CMSC

THE PUBLICATION FOR 3-D MEASUREMENT TECHNOLOGY

IN THIS ISSUE:

WWW.CMSC.ORG

Multiple Reflection Techniques Used to Measure and Model a British Cannon Recovered from the Battle of Yorktown

by Richard A. Uhal, Steven D. Hand, Colleen Brady Cunniffe and Marcie Renner

The utilization of a noncontact laser radar, multiple-reflection measurement technique was employed to generate an accurate 3-D model of a historic artifact, both on exterior and interior surfaces. The artifact scanned was a "four-pounder" British naval cannon (as seen in figure 1) from the deck of a supply ship ordered scuttled in the York River by General Charles Cornwallis just prior to his surrender to General George Washington at Yorktown, Virginia, in the fall of 1781. Measurements were taken directly and with a single mirror on the entire exterior, while the interior bore was scanned using multiple mirror techniques. Difficulties encountered during the scanning process of the bore are described in this paper. Problems were both technical and environmental and included interior illumination, reference tooling ball acquisition, reflection angle and condensation. The data were aligned and processed with the final result being a watertight, polygonal model with an overall accuracy of ± 100 µm (0.004 in.). This model has revealed interesting detail regarding eighteenth-century armament design and period casting techniques and will be used as the baseline to compare the restored artifact to its recovered condition.

INTRODUCTION

The laser scanning was performed at the MAGLEV Inc. research facility (MLI) in partnership with The Mariners' Museum of Newport News, Virginia. This is the second cannon to be conserved by TMM for display on the Yorktown waterfront.

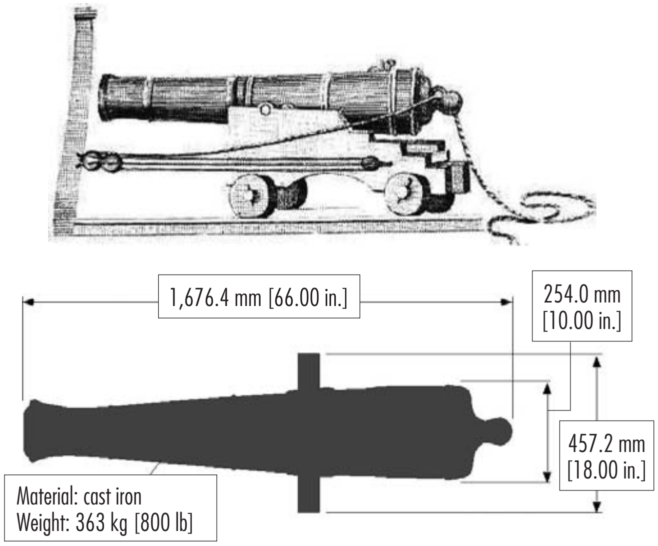


Figure 1. Four-pounder British cannon (approximate dimensions)

PROJECT DESCRIPTION

As a program of mutual support between TMM and MLI, large historical artifacts are accurately measured to generate dimensional records used for documentation before, during and after conservation treatments. Scanning is an ideal documentation technique because it requires minimal handling of the objects. The Yorktown cannon project involved the measurement of all surfaces, including the gun's bore from the breech to the muzzle. This effort entailed the delivery of the 363 kg (800 lb) cannon to the MLI facility; design and fabrication of the artifact support stand; and alignment of the mirrors, jigs, and fixtures needed to take measurements on both outside and inside surfaces. These measurements were then processed into a surfaced 3-D model, as seen in figure 2.

The subject cannon was on board a supply ship of the British Royal Navy under the command of General Cornwallis of the British expeditionary forces in October of 1781. These forces were under siege at Yorktown by the Continental army under command of General Washington, and French forces under the Marquis de Lafayette. Fearing an amphibious assault from the French fleet positioned at the mouth of the Chesapeake Bay, Cornwallis ordered a line of ships to be scuttled parallel to the Yorktown beach to keep the French from landing. When the British surrendered at Yorktown on October 19, 1781, title to all British ships was given to the French. The French recovered numerous sunken vessels, but also left many on the river bottom.

The Yorktown wrecks were not forgotten over time. Numerous historical documents from the 19th and 20th centuries—such as letters, journal entries and even a petition to the General Assembly—refer to the wrecks. The 1931 sesquicentennial celebration of the Battle of Yorktown launched a renewed interest in the sunken fleet. Consequently, in 1934 and 1935, TMM, the National Park Service and the Newport News Shipbuilding and Drydock Co. (now Northrop Grumman) undertook recovery operations in the York River. Over the two years, hundreds of artifacts were recovered from the shipwrecks, including ship's timbers, ceramics, swivel guns, glass bottles and several cannons. The current scanning project measured and modeled one of the cannons recovered during the 1930s expeditions.

MLI measured the cannon using coherent laser radar (CLR), as seen in figure 3. This technology was chosen based on two attributes. The first is the accuracy needed to monitor possible distortion due to the preservation processes. The second is the ability for the CLR focused-beam laser to be reflected from optically flat mirrors. There is no doubt that structured light scanners could provide a much greater resolution for surface deformation analysis. However, the direct measurement capabilities of the CLR keep the data accurate along the entire artifact boundary. This minimizes the transformation uncertainties for each instrument location and reduces the need to "best fit" within the processing software. This also allows for adjusting point cloud and related instrument vectors based on Unified Spatial Metrology Network adjustments prior to exporting final point cloud coordinates for surfacing.

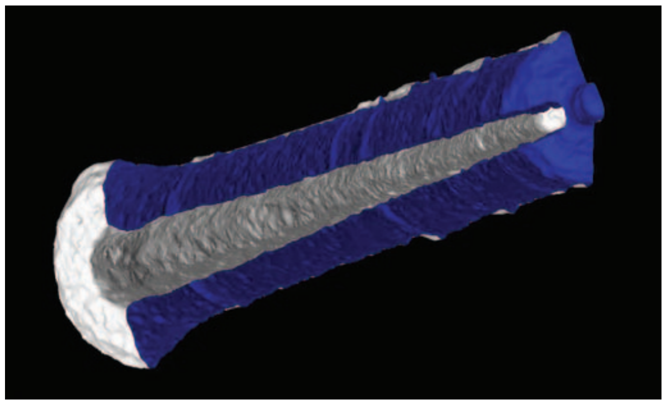


Figure 2. Surfaced 3-D cannon model

The processing of the point cloud data into a 3-D CAD model is necessary for future analysis. These 3-D models are used for comparison with future measurements and also provide a virtual base for study and research. This project employed processing software that performs a meshing routine to optimize polygonal surfacing parameters. Scan data were surfaced and inspected for "holes" and missing "edges" during the measurement process with additional scans being taken to provide 100-percent coverage within a specified maximum point spacing. The final product was a comprehensive 3-D model of the cannon's surfaces.

NOMENCLATURE

The following is a listing of the most common abbreviations and acronyms used in this paper. Items are described in detail. Descriptions of cannon features are shown in figure 4.

- *ASCII*: Text format for point clouds generated by the scanner operating software
- *CAD*: Computer-aided design
- *CLR*: Coherent laser radar
- *CNM*: Control network monuments
- *Closed perimeter scans*: Measurements where the area inside the perimeter is scanned
- *LED*: Light-emitting diode

• *Metris*: Metris USA Inc.
• *Mirror*: An optically flat, first-surface reflector
• *MLI*: MAGLEV Inc.
• *NRK*: New River Kinematics
• *Open perimeter scans*: Measurements where the scan pattern is normal to the line created by the software and followed by the scanner
• *PolyWorks*: Surfacing software by InnovMetric of Quebec, Canada, used for surfacing point clouds and performing inspection details
• *SA*: Spatial Analyzer by New River Kinematics, the operating software used for the CLR scanner
• *Scan grid*: The combination of line and point spacing creating the density of the measured data
• *STL*: Stereolithogaphy polygonal file format
• *TMM*: The Mariners' Museum in Newport News, Virginia
• *Tooling ball*: Grade 25 0.25-in. diameter steel ball
• *USMN*: Unified Spatial Metrology Network; an analysis method that combines measurement systems, taking full advantages of their uncertainty profiles.

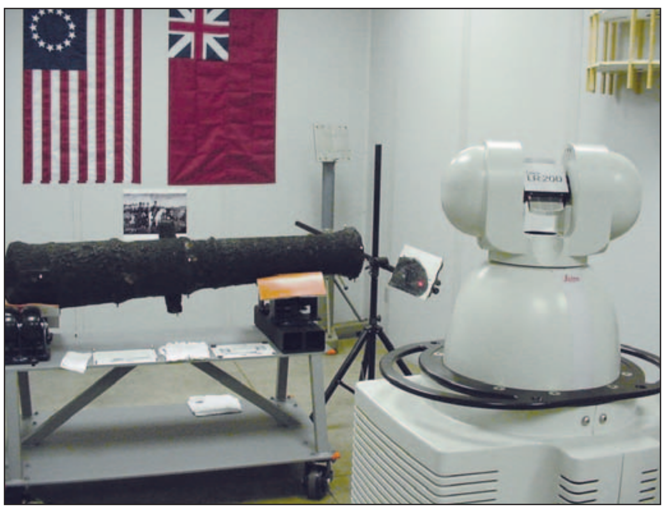


Figure 3. Cannon CLR setup

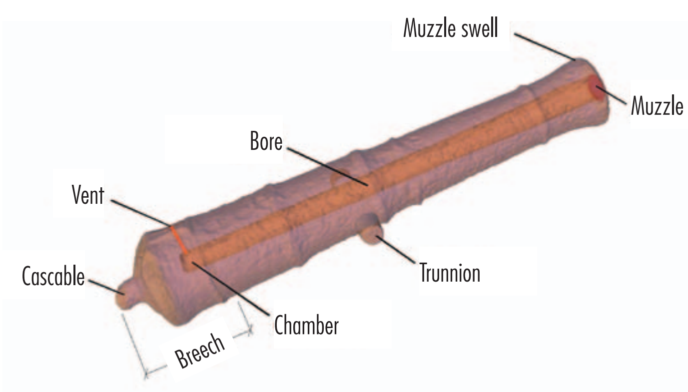


Figure 4. Cannon features

CONCEPT AND TECHNOLOGY

The CLR focused beam has always presented an operator's dilemma for data acquisition. The limited focal depth requires planning for efficient data capture while maintaining sufficient quality points. Couple this with reverse-engineering applications the scanner may be tasked to perform, and you will find that the learned technique of judging scan parameters is more art than science. However, for all of these drawbacks, there is a redeeming quality: The beam can be accurately reflected from a flat mirror.

The early work performed by MetricVision (now a subsidiary of Metris) and New River Kinematics pays big dividends for CLR users who need the ability to see around corners, create better coverage without moving instrument locations, and look deep into holes and inaccessible regions. NRK should be applauded for the simplicity of the "Reflector" option of its Spatial Analyzer (SA) software used to transform reflected measurements. A simple, two-step procedure acquired each mirror vector and kept the operator moving swiftly through the measurement plan.

The second feature of the CLR scanner that makes the "reflective" method possible is the scanner's ability to repeatedly measure tooling balls. The scanner does a good job of repeating tooling ball positions with nearly the precision of a laser tracker.

The procedure for transforming reflected images into the working reference frame, as seen in figure 5, is simple using SA. First, measure the ball directly using the tooling ball mode. You are then prompted to measure the ball's image in the mirror. The software then generates the reflective parameters for the mirror position and angle. One more mouse click will take you into the "reflections" operation, which allows measurement in the working part frame.

Multiple mirror reflections are just as simple; you need only add the second mirror's name during its acquisition. Each additional mirror is referenced relative to the proceeding mirror parameters. As the mirror string increases, the operator must monitor the mirror stability and reflectivity to determine the robustness of the system.

As in all aspects of spatial metrology, geometry plays the critical role in reflective measurements with the CLR. When setting up the reference tooling ball for mirror positioning, it is critical that the measurement envelope does not extend beyond the distance of the ball. However, if this is necessary, it is strongly suggested that the reference ball is one of the control network monuments (CNM) used for project control.

The scanning of the Yorktown cannon used two mirrors for the critical bore surfaces. These are explained in detail later, but it should be noted that the reference-tooling ball was set beyond the cannon cascable for mirror 1, as noted in figure 6. This geometry ensured accurate mirror transformation within the measurement envelope.

The second reference ball placement was more typical of reflective scanning applications found in the field. This is when access restricts any ability to extend the reference beyond the measurement envelope due to line-of-sight conditions. In these cases, the ball must be located nearest the measured surfaces and still be viewable directly from the CLR.

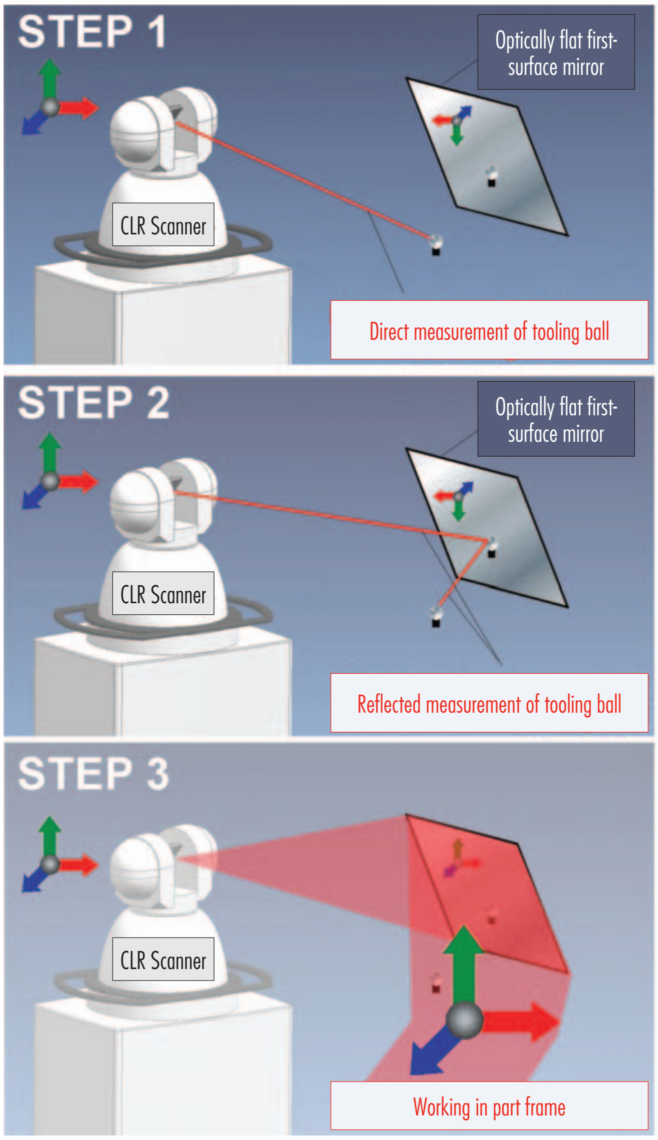


Figure 5. Transforming reflected images into working reference frame

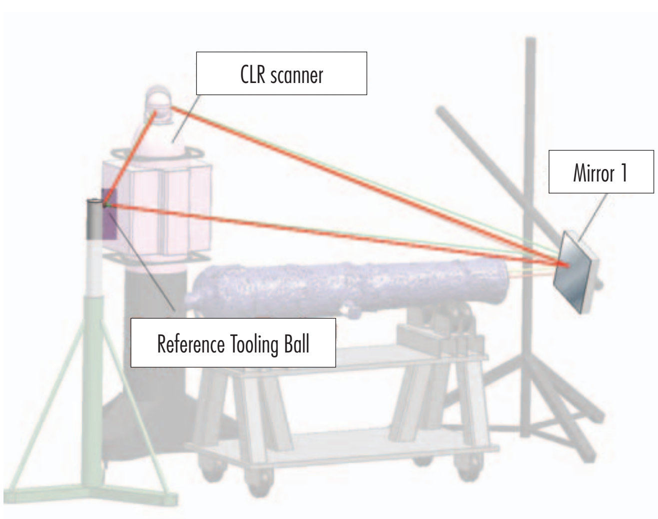


Figure 6. Position of key measurement components

When the best measurement practices are required, multiple points of reference (reference tooling balls) can be used to better "average" mirror transformations. This multiple reference point feature is also very easy to use, thanks to the well thought-out software.

SETUP

Prior to receiving the artifact, a custom-made support structure (as seen in figure 7, original concept) was designed. Due to the weight, which is 363 kg (800 lb), the support had to be robust, mobile and be capable of axial rotation about the cannon's bore.

The completed cart was fabricated at the MLI facilities from 12-mm-thick steel plates and 100-mm-square structural tubing. Hard-locking neoprene wheels were attached to the bottom for mobility and free-rotating neoprene wheels were attached to the top to cradle the artifact while permitting axial rotation.

On delivery day, a museum representative orchestrated the removal of the artifact from the delivery vehicle via a 25-ton overhead crane through the MLI high-bay to the support, which was

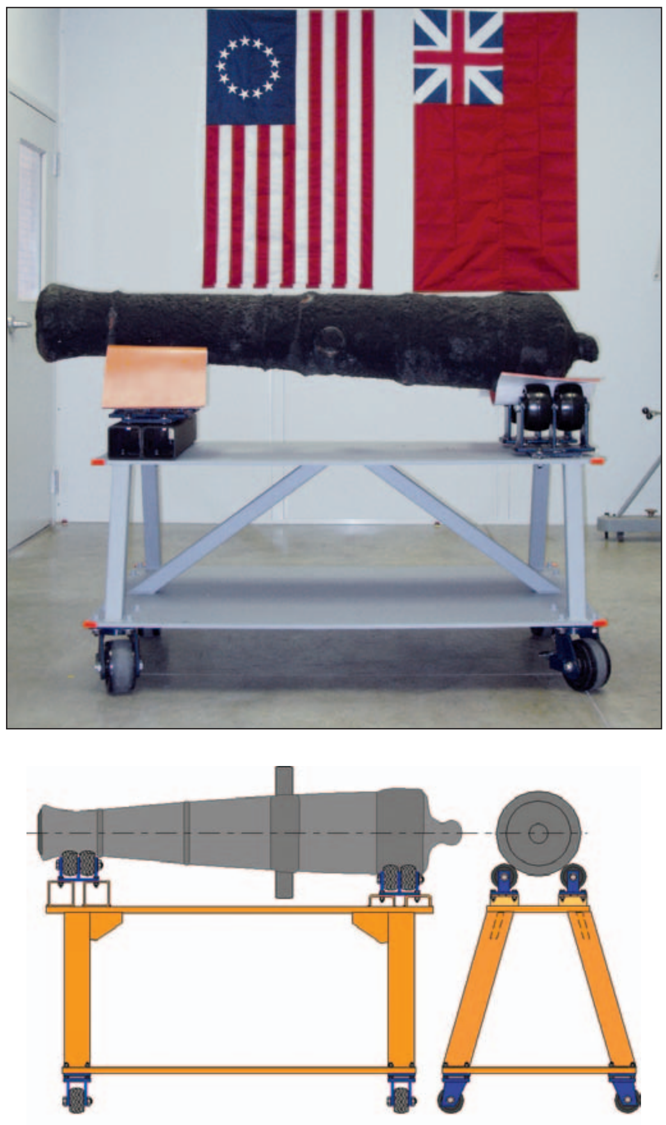


Figure 7. Cannon roller support assembly

positioned near the environmentally controlled metrology room. During this procedure and at all time afterwards, the artifact was handled or touched only while wearing white cotton gloves. Silicon rubber pads were placed on the axial wheels to deter any damage to the contacting surfaces. The artifact was then rolled into the metrology room, where it was allowed to acclimate to room conditions and positioned for ease of scanning.

As scanning progressed, it became necessary to rotate the artifact axially about the bore to gain full scan coverage. At these intervals it was necessary to enlist the help of two or three people who would, in unison, manipulate the artifact into its next position. Great care was taken not to mar the surface or touch any of the CNM tooling balls attached by pull magnets. Extra tooling balls were always added at this point to give greater strength to the CNM.

PROBLEMS AND SOLUTIONS

Scanning of the entire exterior with minimum movement of the artifact proved problematic due to hidden areas on the trunnions and cascable. By reflecting through a faceable mirror, the hidden areas were scanned.

Scanning of the entire bore was requested by TMM. The bore was initially open to a depth of about 200 mm, with the rest filled with corrosion products, mud, rocks and debris. All materials lodged within the bore were removed and returned to the museum. The bore was then brushed and vacuumed to remove any fine particles, as seen in figure 8.

Figure 8. Bore cleared of debris

To acquire data inside the bore, a dual-mirror technique was required, and a method of inserting and positioning the second mirror developed. A movable fixture with a stationary 0.25-in. gage ball was designed and fabricated at MLI, as seen in Figure 9.

The fixture consisted of a carriage holding the secondary mirror and a gage ball permanently attached to the mirror surface. Two stainless steel rods ran through the carriage serving as guideways. At the carriage center, a threaded rod actuated the carriage, allowing positioning along the entire length of the bore. Attached to the bottom of the mirror was an LED light fixture

Figure 9. Carriage and secondary mirror. First attempt.

used to illuminate the bore near the gage ball. Because the light emitted from the LED could not be focused, the LED fixture was removed prior to measuring the tooling ball.

Overall, this scenario did not work. Due to the size of the carriage and rigidity of the fixture, the gage ball was very hard—if not impossible—to locate. In addition, the size of the mirror had to be decreased to fit into the bore. This allowed a very small scan area and was not easily adjusted for angularity.

To address these problems, a second mirror carrier was built, as seen in figure 10. This time a cylindrical brass tube cut lengthwise was utilized to hold the mirror. Attached to the carrier was a thin length of steel graduated at 25-mm increments that was used for depth positioning. A thin wire ran the entire length of the graduated "band" and had a 0.25-in. tooling ball attached at the mirror end. This wire rotated, bringing the tooling ball into view for locating the secondary mirror or to protect the gage ball during carrier positioning, and then rotated out of the field of view during the scanning process.

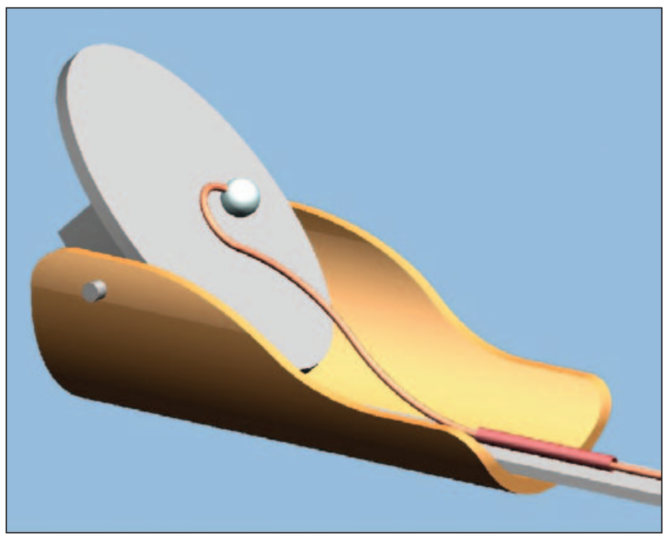


Figure 10. Carriage and secondary mirror. Second attempt.

Figure 11 shows a sectional view of the artifact with the secondary mirror carrier inserted. Generally it is preferred that the gage ball be outside of the measurement envelope, but in this case, due to space limitations, it was necessary to be in close proximity to the mirror and scan surface.

As scanning progressed from the bore to the breech at 25-mm incremental movements of the secondary mirror, it became nec-

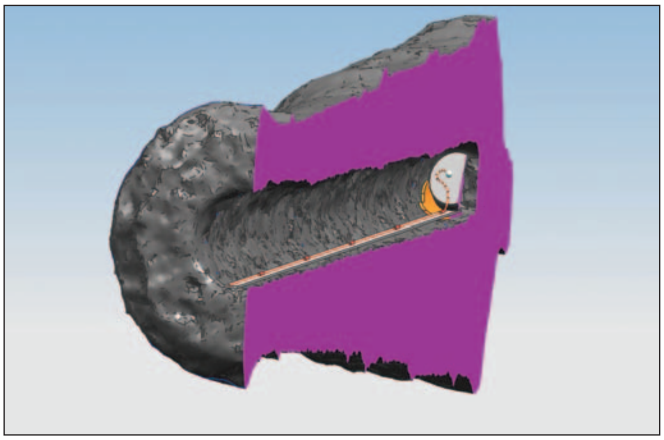


Figure 11. Bore cutaway showing secondary mirror in place

essary to illuminate the movable gage ball. Originally, an LED was attached to the carrier to illuminate the tooling ball, but was removed quickly when it was found to create unwanted ambient light around the area. The solution to illuminating the tooling ball was to insert an LED penlight on a thin rod, and position it as required to illuminate only the area needed at that particular location to see the tooling ball. This solution was adequate and was used to complete the interior scanning.

Because the artifact had been submerged and the bore packed with debris for so many years, the oxidized and porous interior surfaces caused an unanticipated highly humid environment in the depths of the bore. This resulted in a fogging problem whenever scanning at any depth beyond 450 mm from the muzzle. The fogging was difficult to diagnose because the mirror was hard to view while in the bore. After some experimentation, we discovered that the fogging occurred after the carrier had been removed from the bore and allowed to return to room temperature. Once it was returned deep into the bore, the warm, humid air condensed onto the cooler mirror. By piping in some compressed air through surgical tubing, we were able to control the condition and continue.

Interior surface roughness (as seen in figure 8) caused the carrier to sometimes rack axially or radially, causing holes in the data. The only solution was to manipulate the carrier into a position for scanning that would allow for overlap in the unscanned areas. In figure 12, a "patchwork" of point clouds demonstrates the number of clouds (approximately 200) that were required for full coverage of the bore.

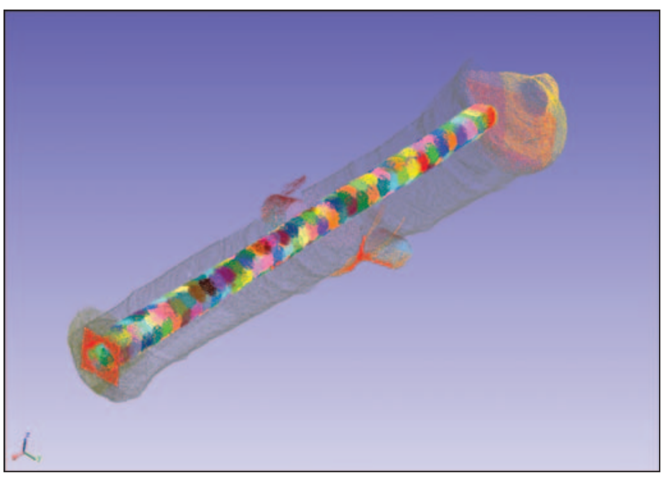
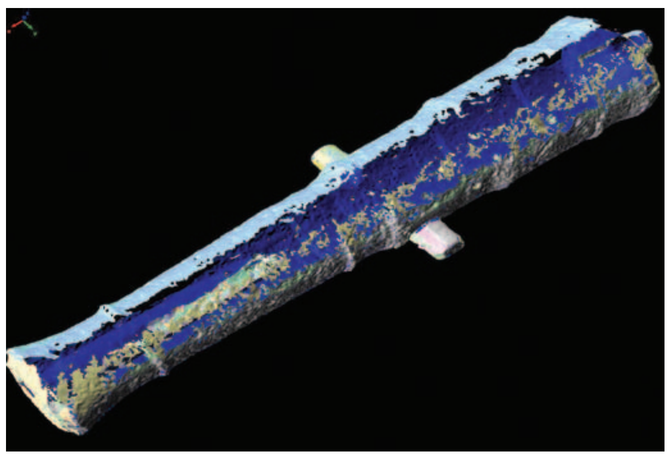


Figure 12. Full bore coverage required a patchwork of point clouds

DATA PROCESSING

The scanned point clouds were processed into a 3-D CAD model using typical reverse-engineering steps. The initial point clouds were edited and then exported as ASCII point clouds using SA scanner software. The ASCII point clouds were then imported into a surfacing and inspection software—PolyWorks by InnovMetric. The data were then aligned, surfaced and finally polygonized into numerous 3-D formats for use in analyzing, reproducing and archiving so that future conservators could perform future measurements, comparisons and analyses.

Because the CLR measures discrete points, all measured data are accurate to within the manufacturers' specifications and the transformation error of the control network. This condition provides a head start in determining actual point-cloud alignment when initially processing data. As each point cloud is imported into the alignment module, the operator selects the parameters for surfacing. Polygonal leg length, overlap tolerances and surface direction require the greatest amount of consideration. Tweaking alignments can also be achieved in this step, with the consideration of adequate surface features for fitting. Most models can



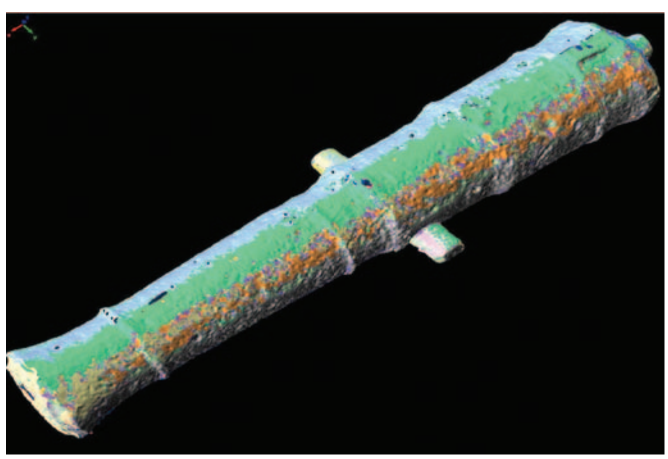


Figure 13. Surfaced model

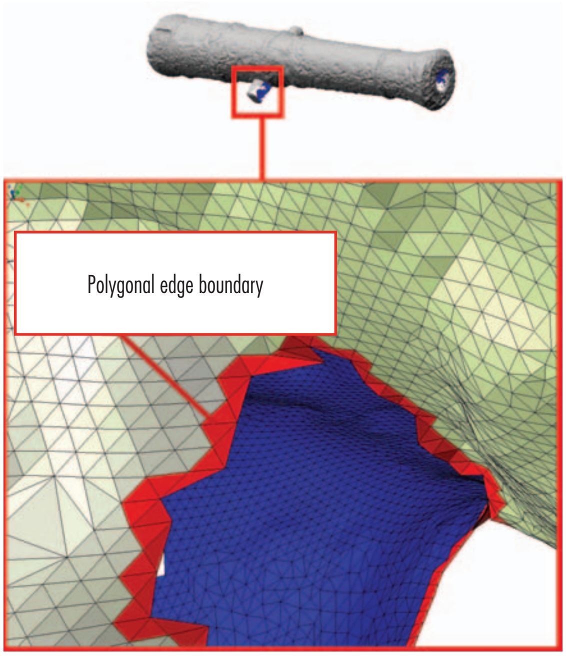


Figure 14. Polygon edges are used to detect and fill holes.

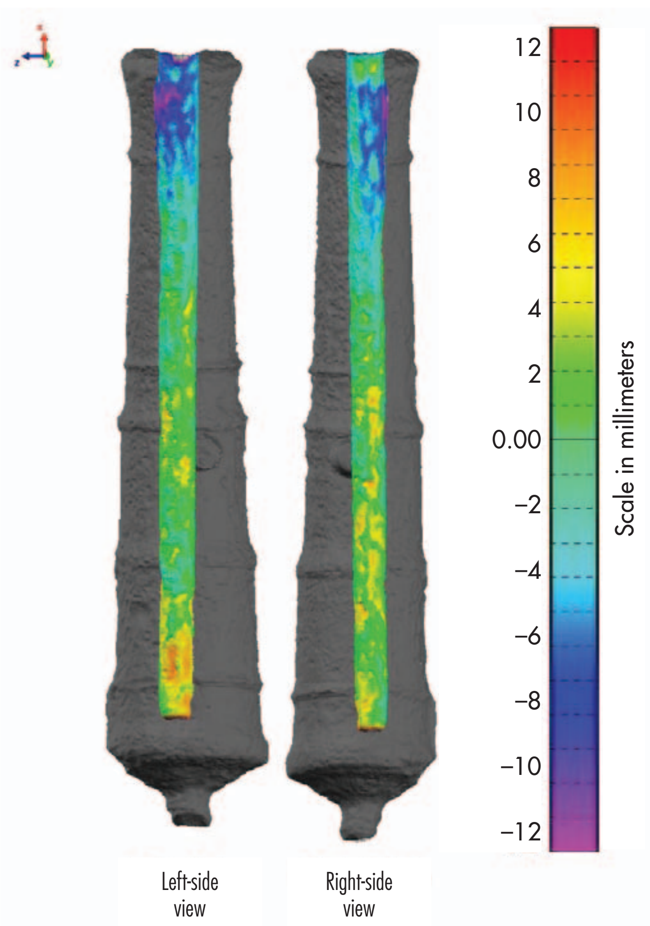


Figure 15. Bore taper

benefit from best-fit adjustments if they are properly restrained and have adequate features for fitting. With CLR data, this step is usually bypassed in favor of using the actual control network transformations, as seen in figure 13.

Surfacing of the point clouds was performed by polygonizing the mesh generated by the previous steps. The cannon model was then brought into an editing program to check for polygon conditions, such as intersecting triangles, islands and holes. (See figure 14.) In this example, the hole required additional scanning, but for the most part, holes are automatically filled and, in the case of the cannon scan data coverage, the model took little work to produce a watertight model.

Surfacing software programs usually have the ability to analyze models and provide information regarding "water tightness"

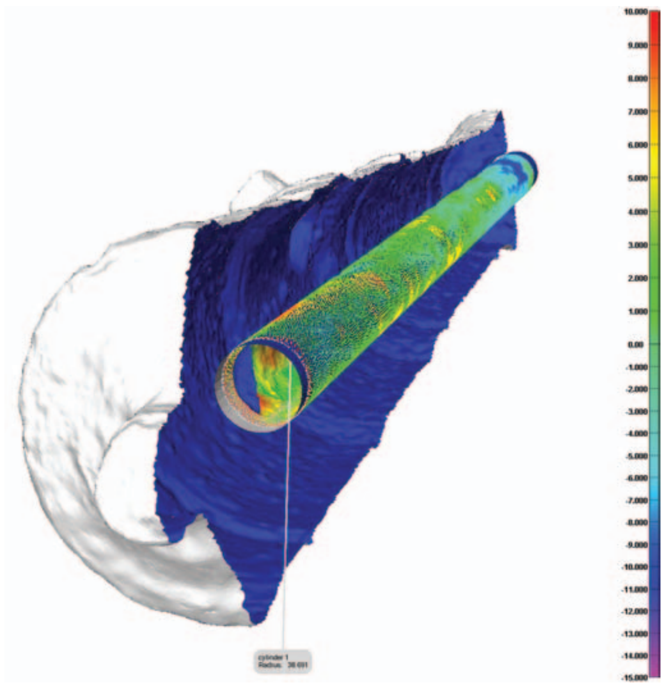


Figure 16. Bore taper viewed from chamber

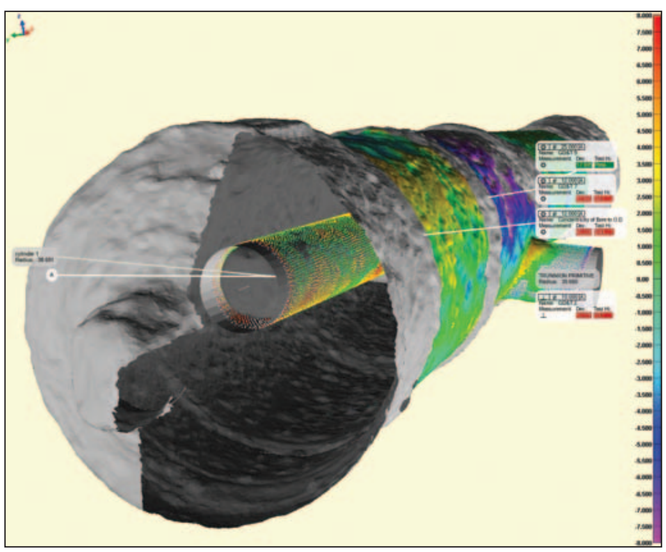


Figure 17. Bore GD&T

based on the presence of exposed polygon edges. This is true with PolyWorks, and the tools allowed the operator to search out these openings for edit and repair.

RESULTS

The measurement of the cannon provides a fixed 3-D model, in time, that can be used for all of the reasons previously discussed. The following is a review of the actual results of generating the model. Overall, the project took 24 days to complete. This included the planning, fixture design and field corrections to problems. Other scanning particulars include the following:

- Total points measured (scanned): 7,893,426
- Total files: 260 point clouds
- Control network RMS: 0.0454 mm
- Average point standard deviation: 0.0325 mm
- 3-D model size: 1,341,101 polygons

After 3-D model generation, the data were analyzed for characteristics in the cannon features. One very interesting aspect of the cannon's condition was its bore. When viewed in cross section, the bore appears tapered. This condition can be observed and quantified by fitting a cylinder, described as a primitive, to the data and generating a color comparison of the model surface to the primitive, as seen in figure 15.

As shown in figure 16, the surface appears to taper from the +2 mm range in the chamber area (bottom of graph) to a –2 to –4 near the muzzle (top of graph). When fitting a cone to the bore, an angle of 1.03° is shown as the taper.

Other aspects of the artifact's manufacture can be determined by generating GD&T conditions regarding the cylindricity of the bore, concentricities to outside surfaces and perpendicularity of features, as seen in figure 17.

Final results of this exercise will be realized upon the rescanning of the cannon after preservation activities and treatment. At that time the two images can be compared and insight into process applications and their effects on antiquities can be dimensionally validated.

ACKNOWLEDGMENTS

The authors of this paper would like to thank The Mariners' Museum of Newport News, Virginia, and MAGLEV Inc. for their support of this project. This scanning project is a volunteer effort designed to better understand the value of high-accuracy metrology and its use for supporting the conservators who are tasked to bring these treasures to the public, and maintain them for future generations.

Also noted, with great appreciation, are the work and efforts provided by New River Kinematics for the software and algorithms used for multiple mirror applications, and Metris for its contribution of the software.