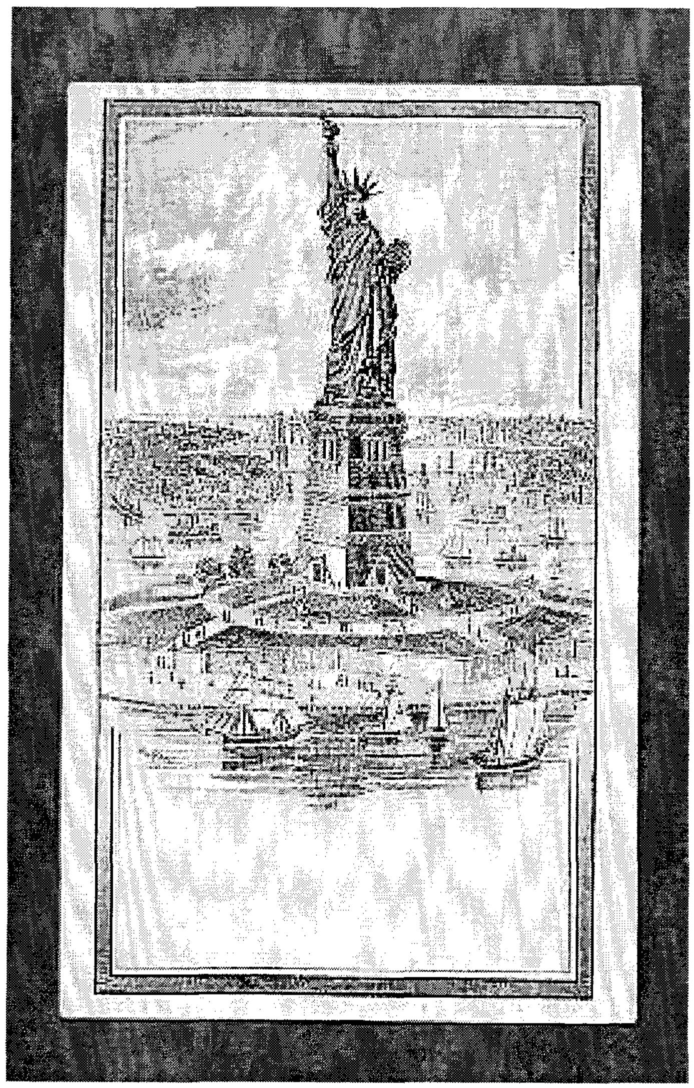
Preserving Liberty:
3-D Laser Scanning the Statue of Liberty Monument

ELIZABETH I. LOUDEN
GLENN E. HILL
JOHN P. WHITE
Texas Tech University

OVERVIEW OF THE PROJECT



In January 2001, Paul Dolinsky and Blaine Cliver from the Historical American Buildings Survey (HABS) representing the National Park Service (NPS) contacted Professor John White, HABS Fellow and professor at Texas Tech University about using the recently acquired 3-D laser scanner to record the exterior measurements of the Statue of Liberty.[1] The task would be to produce the United States' first-ever architectural drawings of the exterior of the Statue of Liberty.

Gathering accurate exterior surface information was obviously impossible to attempt by hand measurements without extensive scaffolding similar to the 1985 project. That scaffolding was used to gain access to areas of metal deterioration and to do the necessary restoration work. The interior stairs and armature structures were delineated in 1995 under the direction of Eric Deloney of Historic American Engineering Record (HAER) and later archived in the Library of Congress. The skin of Liberty is a 2.37 mm (.09330 or 3/32 inches) thickness of copper; so it was agreed that typical architectural plans and sections were not appropriate. Cross sectional cuts taken at one foot increments and eight elevations will adequately represent the form of the statue for the purposes of the HABS requirements. After further consideration about safety of personnel, the project received the "go-ahead" by NPS officials, contingent upon proof of data accuracy.

The next few months were spent in discussion and planning for the task. A March, 2001 pilot study was conducted by Associate Dean for Research Elizabeth Louden, and Associate Professor Glenn Hill, with the assistance of a Cyrax technician, Tim Woodruff. Observers from NPS were also on hand to receive assurances that the feasibility of the idea was sound and others.[2]

This initial test scanning of the JA Ranch proved to the researchers that 3-D laser scanning could provide accurate, fast and reliable documentation data for historical architecture. The JA Ranch drawings were ultimately a combination of scanner information and hand measurements to create the HABS drawings.[3] The researchers had become proficient at gathering the data, but the interpretation, analysis and final results proved to be the most illusive aspect of the project work. The Statue of Liberty project would test planning and analysis skills to the highest degree thus far.

"The plan is useless – the planning is indispensable."(Dwight D. Eisenhower – abridged)

SCANNING THE STATUE OF LIBERTY

Phase 1 – March, 2001
Preliminary Field Testing and Conversion of data Summary

Given the primary research goals of the testing the use of the 3-D scanner on non-linear geometry at a monumental scale, the

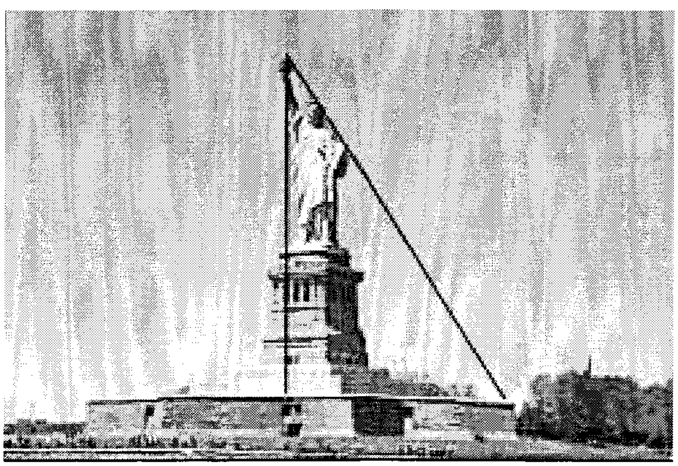


Fig. 2. Scanner distance and angle of measurement.

first task was to test the feasibility of the 3-D laser scanning for use on the Statue. Paul Dolinsky from HABS coordinated personnel from NPS, Cyra Corporation, and Texas Tech University for a March, 2001 test scanning at Liberty Island. The primary purpose of the March visit was to test the accuracy of the scanner at distances of over 300 feet and establish the logistics of scanner placement and procedure. The Cyra manufacturer verified the scanner accuracy for distances up to 164 feet (50m); however, from the scanner head to the tip of the torch the distance ranged over 350 feet. A standard procedure was used to place registration targets on the Statue and Pedestal and their locations surveyed with a Leica Total Station instrument. The targets served two purposes; first, to provide registration points for registering the multiple sets of scan data together and second, to provide comparative points for the accuracy verification. The Statue was scanned from four typical locations and HABS staff surveyed the distances between each of the registration targets. The measurements between the registration targets obtained from scanner point clouds and the Total Station survey points were compared for accuracy.[4] For the stationary targets placed on the crown and pedestal accuracy fell within the required .25", but there were some discrepancies between target distances on the torch of up to 2.5". Compensation calculations were made for the movement in the arm and torch attributed to the wind and metal expansion. The original torch, now located in the rotunda of the pedestal to the Statue, was scanned to supplement questionable data at the torch.

Phase II July 2001 to December 2001
Success at gathering the 94 million data points in 4 days

Based on the March test and planning visit, the team determined that the statue could be documented in three phases. Approximately 60% to 70% of the statue was visible and could be scanned from the promenade level of Fort Wood (the roof of the visitor center). Another 20-30% could be scanned with the use of scissor scaffolding from the observation deck level at the top of the Pedestal. The remaining 10-20% would have to be interwoven with data gathered with overhead photogrammetry or other technologies.

From June to late July 2001, preparations were made for the phase one scanning from the promenade. Equipment was again shipped and travel plans coordinated. The planning of the project scans was carefully mapped out to insure adequate overlap from one scan position to another. Placement and position of registration targets was critical. This site analysis determined that thirteen scans would be taken from the extreme points of the Fort Wood promenade level thus reducing the laser beam angle of incidence. The apex of each wall provided the most distant position from the Statue and the most visibility of the surface. To scan from the ground level of the island would have limited more visibility of the Statue and extended the distance that the beam had to travel. The promenade level provided the best accessible positions for the scanner locations.

The team arrived in New York on Sunday, 29th July, 2001. The first day on Liberty Island was spent assembling equipment and establishing scanning procedure and logistics. Elizabeth Louden and volunteer assistant, Karen Hughes worked with NPS personnel to resolve logistical matters of assess to security areas, power generation, equipment storage and public management. Glenn Hill and two students, Jared Wright and Jon Gamel from the Texas Tech University College of Architecture, spent the majority of the day verifying scanner positions and placing registration targets.[5] The triangulation required over the vertical distances demanded careful placement of targets

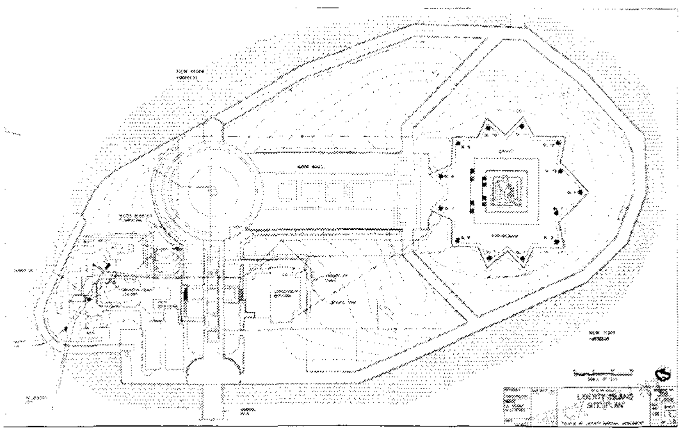


Fig. 3. Plan of Liberty Island, scanner location positions indicated by points at the apex of the star-shaped Fort Wood promenade level.

relative to the base of the pedestal and the angle of incidence for the laser beam. Thirty-two targets were placed around the exterior of the pedestal, crown and torch. These targets are used to register data between the thirteen different scan locations; it was late afternoon of the first day before the first scan was started.

Day two accomplished only three of the thirteen scan locations. The team had planned to do a minimum of three to four scans a day based on previous experience with other scanning projects such as the J.A. Ranch. The team was then three scan locations behind schedule. Professors Louden and Hill decided that the team would work in two shifts to allow continuous scanning in eight hour shifts, taking advantage of the first NPS ferry in the morning and the last in the evening. Days three and four went smoothly as the team became more experienced with the procedure. This allowed all planned scans to be completed as well as the survey of the registration targets. With great relief, the team completed scans a day earlier than scheduled. At the end, the biggest overall headaches came from the simple issue of battery re-charging and power back-ups.

The team gained valuable knowledge from this phase of the experience:

1. The planning was indispensable, but continuous flexibility to adapt to new situations was absolutely necessary. Team preparations during the March 2001 scanning test and establishment of a planning procedure prior to the July 2001 scanning, allowed the team to clearly understand the technical issues before them. The researchers believed the planning alone reduced the time needed on site and gave them the knowledge and understanding of the situation to quickly make adjustments to the procedures.
2. Access to alternating current (A/C) power is essential. While the scanning system is capable of running off batteries, scanning speed also significantly decreases as the batteries discharge thereby reducing equipment performance.
3. High profile public places such as this required someone full time to deal with the public. Coming prepared with printed information as hand-outs would have alleviated the necessity of repetitively answering many questions.
4. Acquire more data than may seem necessary to avoid a return trip. Reduced field time is one of the most cost effective aspects of the 3-D scanner use, therefore data redundancy acts as back-up information.

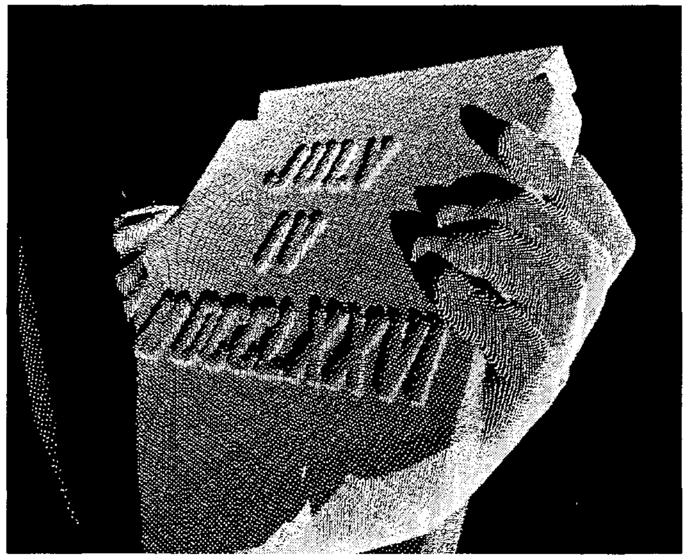


Fig. 4. Close up view of the Statue of Liberty tablet showing details of July 4, 1776 tablet date.

TURNING POINT CLOUDS INTO 3-D MODELS

Registering the Site Data

Once the team collected scan data (often referred to as a point cloud) at the site, the next step was to take the various data sets and merge them together. The statue was scanned from thirteen (13) separate locations. Each location, called a *scanworld*, has a different coordinate system and must be merged into one contiguous point cloud to generate the 3-D model. A scanworld contains seven scans for a total of 7,000,000 points.

The two most common methods of registering the separate point clouds are target registration and software registration. The first method uses triangulation to register the point clouds together. A minimum of three special reflectors or geometric targets are placed in the scan field during the scanning process. These shared targets between the two scans become the registration points from which the scans are merged. By connecting three registration points from one scan to the same three registration points in another scan, the two independent scans are accurately merged together. The software registration method aligns the different point clouds by statistically evaluating overlapping sections of the point clouds. Of the two methods, the software registration is easier and completes the combination of information in a much less tedious manner than the triangulation of targets method.

The choice of a registration method depended on ease of alignment, time required, and the degree of accuracy. Ultimately, accuracy was the primary question for both the distances involved and the final project rendering issues. The accuracy limitations of the scanner are predictable and any error spread across 50 to 300 feet obviously increases the inaccuracy many times. For example, a difference in measurement between the same two registration points of .25″ (6mm) from one scanner position to another. If the distance between the targets is 10 feet the resulting error at 50 feet becomes 1.25″. As slight errors are compounded, the difficulty increases for accurate registration of point clouds.

The first attempt of registering the Statue point clouds used the target registration process and triangulation method. During the September and October of 2001, work began to combine the point clouds. Early attempts to work with all thirteen scan-worlds together resulted in errors of 39.37″(1m) to 390.7″(10m). Jared Wright, under the direction of Professor Hill, struggled with a frustrating and tedious task of determining the source of the errant data. By isolating and gradually adding or removing specific files of data, he eventually was able to reduce the margin of error to between 0.27559″ (.007m) and 2.36220″ (.06m). Although this was closer to the required accuracy, it was still not acceptable. Hill began to research software that would register the point clouds without requiring target alignment.

Two softwares were evaluated for this purpose, *Polyworks* by Innovmetrics and *Geomagic Studio* by Rainbow Geomagic. A comparison set of data was extracted for use in both softwares.

Fig. 5. First attempt to register four scans together shows errant target registration.

The softwares performed at equivalent accuracy levels, but *Geomagic Studio* was chosen for its ease of use and price to performance. From November 2001 to March 2002 several test were done with the data. In December 2001, all the funding was depleted leaving no funds to retain graduate students. A lack of funding for the purchase of new software and difficulties in establishing acceptable alignment of the scans created continuing delays. In addition, as the point clouds were registered together the difficulty in manipulating them increased. High performance workstations had to be purchased to continue the work with the huge files.[5]

By May 2002 a data set of 16,000,000 points had successfully been registered. This represented point clouds from each of the 13 scanning positions with points spaced approximately two (2) inches apart. In February 2003, funded by a Graduate School scholarship, another research assistant "Bear" (Wei Xiong) took the full 98,000,000 points and registered them into a single point cloud, the first 3-D model from a complete data set. As the software finds the points, the overlapping triangulation of points was averaged producing a registration error of .024″(0.00061m).[7]

The most important information gained from data analysis and process evaluation to date is as follows:

1. The non-uniform geometry of curvilinear surfaces equates to reduced accuracy when relying on overlapping target registration.
2. The specific circumstances of a site may require the use of targets. Documentation of ruins such as the Chaco Canyon outlier sites, required the use of target registration. The opposite sides of the ruin could not be connected with overlapping scans due to their location along a precarious ridge.
3. Software registration of point clouds is efficient, accurate and more preferable to target registration methods. Multiple point clouds can be registered with software ten or more times faster than target registration.
4. Software registration is as accurate, if not more accurate in most cases, than target registration methods.
5. A system of 'checks and balances' that combines multiple methods (total station survey and the use of reflective targets) although apparently redundant, assures accuracy.

Converting Point Clouds to Surfaces

In the next step of the process, researchers converted the registered point clouds into a polygonal mesh. This process known, as tessellation, is a complex 'connect-the-dots' game. Conceptually, one point in the cloud is connected to its nearest neighboring point with a straight line. Three connected straight lines define a triangular surface or a simple polygon. The

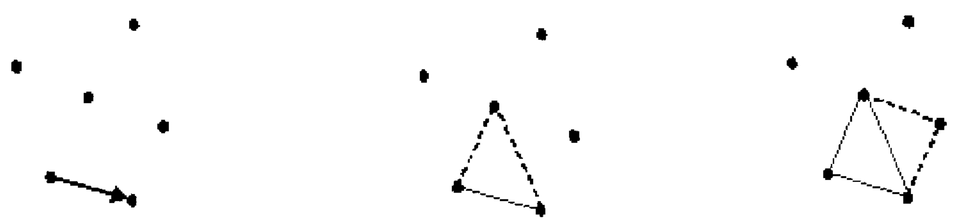


Fig. 6. Tessellation process diagram describing polygonal mesh process.

process continues until a mesh of triangles is created from the points (x, y, z coordinates in space) in the cloud.

The ability to create polygonal meshes from point clouds was a requirement for the software programs under review. Working with Robert Black, an application engineer with Rainbow Geomagic, the first registered point cloud (16,000,000 points) was converted into a polygonal mesh. The resulting polygonal mesh contained 9.6 million vertices and 4.9 million polygons. Transferring this polygonal mesh into a Computer-Aided Drafting (CAD) software to extract two-dimensional drawings was the next step. Unfortunately, none of the conventional CAD software (AutoCAD, Inventor, Rivet, Microstation) could open the file. The problem seemed to lie in the memory limits of the Microsoft Windows operating system. Currently, researchers are seeking other solutions such as using Unix (Catia) based CAD, decimating (removing redundant data) the polygonal model to a more manageable size, converting the polygonal model to a Non-Uniform Regular B-Spline (NURBS) model, or breaking the model into manageable sections.

Attempts to create a polygonal mesh from the single 98,000,000 points have been unsuccessful to date. The Microsoft Windows operating system allows a single application to access 2MB of data at a time creating a significant resource limitation.

From Polymesh to Drawings

The final step of the process will be to create the drawings as the deliverables for the contract with HABS. The horizontal section drawings cut through the surface at one foot increments are relatively simple to provide once the polymesh is created. Geomagic Studio will extract polyline cuts through the polygonal model of the statue, producing the cross-sections. A complex contour mapping of more than 300 line drawings, the equivalent of plan and section documentation, will be produced. The elevation drawings are more difficult to produce to match HABS rendering standards. These will be produced from eight vantage points around the model to provide a comprehensive view of the curvilinear surfaces.

There are fundamentally three approaches to generate two-dimensional elevation drawings from the datasets. The overlay method was utilized in the initial scan project at the J.A. Ranch. Here the scanner operated only as a 2-D measuring device. Registered point clouds were not converted to polygonal models. Instead, the point clouds were used in as overlay drawings. By cutting portions of data that correlated to specific views of the ranch building and referencing them to AutoCad, tracing the point clouds (the point clouds can be selected and snapped to in AutoCad), more accurate drawings resulted than is possible even with photogrammetry. The lack of definitive edges on the geometric form of the Statue made re-matching cut edges extremely difficult. The overlay method works well with uniform geometry (such as rectangular structures), but non-uniform structures add new levels of complexity.

The other two methods involve converting the point cloud into a polygonal mesh. The first technique takes the polygonal model into a rendering and imaging program, and then executes a high resolution image of the orthogonal view. The orthogonal image can then be used as a scaled underlay image and digitized in a similar manner to photogrammetric methods. To date, the team has been working with the small polygonal model (4.6 million surfaces) that can be read by an imaging program (3-D Studio MAX, Maya). The complete 98,000,000 point set has not yet been converted to a polygonal model although a dialogue with researchers in Italy, who developed software to create scaled high-resolution renderings of the *David* by Michelangelo for the Digital Michelangelo Project at Stanford, is in progress.[9] These methods of handling large amounts of data may be incorporated from that project.

The final alternative and most preferable may be to extract two-dimensional elevation drawings from a hidden-line procedure in a CAD program or the scanner software. Currently we are exploring the conversion of polygonal models into a NURBS. The NURBS model should be able to represent curvature of the

Statue more efficiently and provide a more accurate description at a smaller and more compact file size. This NURBS model could then be brought into a CAD-CAM software and treated like a very large mechanical object. The latest procedures have created a model that results in 11 million triangles, at which point, the file becomes unmanageable.

Decisions on rendering techniques of the 3-D model are being discussed. Numerous holes or gaps in the model will have to be filled in order to complete the NURBS conversion. John White has reviewed the polygonal model and has documented where filling the model would be acceptable. Valid research methods require development of a rendering system that will represent the areas that have been filled or interpolated by computer algorithms in the final documentation. Representation techniques that allowed continuation of the surface rendering, yet denote fills, have not conclusively been reached. The final step involves producing a completely computer-rendered model and at least one drawing that is a combination of the basic computer outline with rendering enhancement. The final output scale has yet to be determined between the TTU researchers and HABS, but likely will be similar to the output scale of the Washington Monument documentation.

Filling in the Missing Data

In December of 2002, HABS completed a helicopter fly-over to provide aerial photogrammetric images. Digitizing the images will be the final step in completing the missing data areas, most notably the areas on the head and chest. Another trip to Liberty Island will be required to scan the bottom of her gown and parts of her feet. The scanner will need to be elevated to a position that allows a view of the Statue base.

CONCLUSIONS: STATUS OF THE PROJECT

Overall, the decision to use the scanner for this project was a sound and reasonable determination. The obstacles are primarily those of large and complex data sets. Although comprised of smaller data sets, procedures developing on other historic building documentation projects currently underway (6666 Ranch, Goodnight Ranch, Daniel's Ranch and others) inform and contribute to the complexities of the Digital Statue of Liberty project. The actual time and project cost reduction with the use of the scanner over traditional methods to record historic buildings has not been assessed, although clearly the cost of scaffolding the entire structure again was cost prohibitive leaving the laser scanning the most viable option. Safety benefits are clearly superior when recording monumental structures. Accuracy levels are higher as well as offering quick and efficient measurement tools, but the unanticipated problems with data manipulation are costing large blocks of time in analysis and process development.

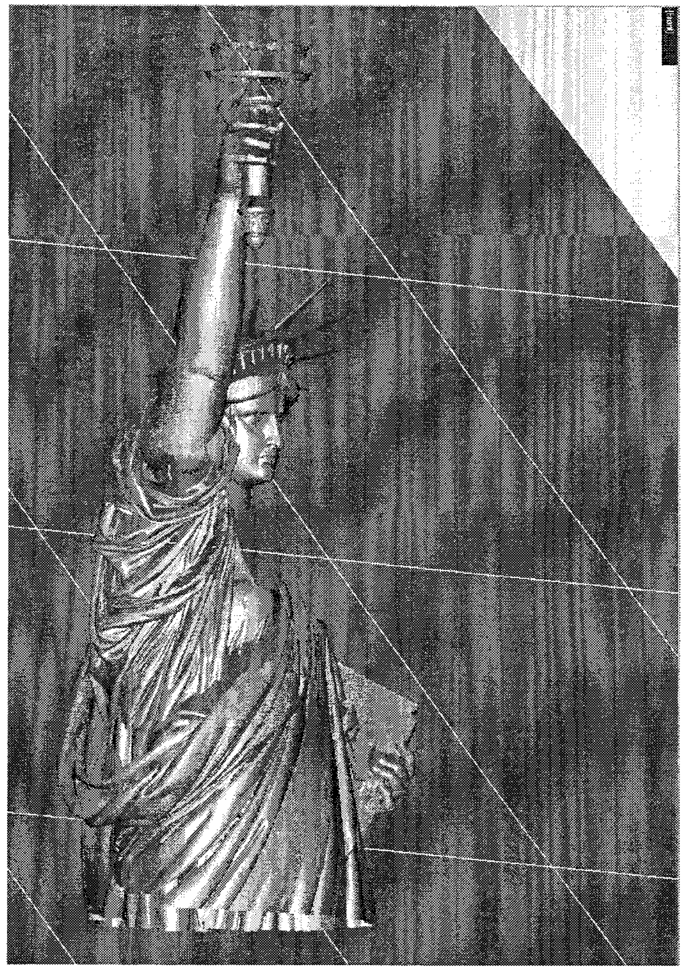


Fig. 7. Completed 3-D model compared to a photograph of the actual statue.

In his October 28, 1886 acceptance speech, President Grover Cleveland said, "We will not forget that liberty here made her home; nor shall her chosen altar be neglected." As part of that pledge not to neglect liberty's altar, the National Park Service is searching for effective ways to preserve Lady Liberty. One aspect of the preservation effort is to safely, and to accurately record the exterior surface of the statue. Another part of their charge is to constantly move forward with the development of historic building documentation procedures and processes. Their commitment to keep abreast of new documentation techniques complements the University mission to stay at the forefront of technology and educational opportunities. The combined efforts of these agencies will help to ensure the development of appropriate techniques and effective preservation strategies. Continued research is needed to formalize the procedures for acquiring and manipulating the data as well as to complete the entire statue documentation.

There are some things which cannot be learned quickly, and time, which is all we have, must be paid heavily for their acquiring. They are the very simplest things, and because it takes a man's life to know them the little new that each man

Fig. 8. Model showing surface mapping and areas of missing data.

gets from life is very costly and the only heritage he has to leave.
–Ernest Hemingway (1899-1961)

BIBLIOGRAPHY

Bagchi, Sumantra. *The Digital Reflection: Implications of Three Dimensional Laser Scanning Technology on Historic Architectural Documentation.*, Master Thesis, Texas Tech University, 2001

Jensen, Henrik Wann. Marschner, Stephen R. Levoy, Marc. Hanrahan, Pat. "A Practical Model for Subsurface Light Transport." *SIGGRAPH Conference Proceedings.* 2001.

Hill, Glenn E. "Immortalizing An Artist's Handiwork: Digitally Scanning Lady Liberty." *Professional Surveyor.* 22-2 (2002): 6-10.

Edwards, Kent. *Proceedings Association for Preservation Technology*, Washington Chapter, GSA Headquarters, Washing, DC. "Existing Conditions Documentation Using Lasers." (September 2001).

INTERNET RESEARCH

http://graphics.stanford.firenz.it/projects/mich. Accessed December 29, 2001.

http://www.arch.ttu.edu/digital__liberty Accessed December 29, 2001.

http://www.endex.com/gf/buildings/liberty/libertyfacts.htm, pg 2. Accessed January 1, 2002.

http://xroads.Virginia.edu/~CAP/LIBERTY/lady__bar.html Accessed January 1, 2002.

http://web.star-telegram.com/content/fortworth/. . .fw010402-1125-XB001-4html

CORPORATE RESOURCES

http://www.vexcel.com/fotog/index.htm accessed January 11, 2002.
http://www.carlsonsw.com/
http://www.cyra.com
http://www.enr.com/itnews/it120309c.asp. Accessed January 1, 2002.
http://www.innovmetric.com/home__en.html
http://www.paraform.com/
http://www.via-pc.com/
http://memory.loc.gov/HABS/HAER Prints and Photographs division of the Library of Congress. Accessed 01/05/01.

TEAM/RESOURCES

Historic American Building Survey Division of the National Park Service provided project funding. Phase I for the preliminary trip covered the travel cost and shipping. Phase II project funding capped at approximately $40,000. Currently, we are in the process of seeking funding to continue the documentation of the remaining 30% of the statue.

PROJECT PARTICIPANTS LIST

Co-Principles

Associate Professor Elizabeth Louden, Project Supervisor, TTU
Associate Professor Glenn Hill, Technical Supervisor, TTU
Professor John P. White, Project Consultant, TTU

Consultant

Karen Hughes, Hardy, Heck, Moore, Inc., Austin, TX

Student Participants

Jared Wright
Jon Gamel

HABS

Blain Cliver, Chief HABS/HAER
Paul Dolinsky, Chief HABS
Dana Lockett, HABS/HAER

NPS

Diana Pardue, Chief, Museum Services Division
Liberty Island and Ellis Island NPS

Equipment

Cyra Technologies
Tim Woodruff
VIA PC with sunlight readable display
Leica Total Station
Carlson Survey Software, *Tsunami*

AutoCad

Locations
Liberty Island, New York Harbor Architecture Research Center.
College of Architecture, Texas Tech University, Lubbock, TX

NOTES

[1] Scanner Specifications – The 3-D laser enables the efficient capture of detailed descriptive surface geometry with its capability of gathering 1 column/sec @ 1,000 pts/column @ full Field Of Vision (FOV) and a 2 column/sec @ 200 pts/column @ full FOV with a single point accuracy of * ± 6mm @ 1.5m-50m range, 1 sigma. (*Standardized test conditions and statistical data analysis methods available from Cyra Technologies, Inc.) The modeled surface precision is * *± 2 mm with a maximum scan vertical density of .25 mm @ 50m and a maximum horizontal scan density of .25 mm @ 50m in a 1,000 points per vertical column. (* * Subject to modeling methods). The scanning optics includes dual mirrors controlled by random access timing devices. It is protected by metal housing and a precision glass lens that shields the internal mechanisms. The video targeting supports a 480 x 480 color resolution. The laser type is a green, pulsed, proprietary microchip that is a safety Class II (ref. CFR 1040), eye-safe, except in the event of direct, long-term exposure.

[2] Following the initial visit, contract obligations and negotiation of a five year Memorandum of Agreement took another three months. http://memory.loc.gov/HABS/HAER Prints and Photographs division of the Library of Congress. Accessed 01/05/01. See Project Participant List for complete listing.

[3] The previous year had been spent learning the process of combining and interpreting scan data into measured drawings of the J.A. Ranch homestead. The historic JA Ranch in the panhandle of Texas although complicated to record, was a simple task in comparison to the new challenge before them. The J.A. Ranch is the original home of John Adair, and the headquarters for the ranch that he and his partner, Charles Goodnight of the Goodnight-Loving trail (1866-1890s), built in 1876. The project run by Professor John White used 3-D scanning technology to document the main house. The drawings of this project are in final preparation for submission to the Library of Congress. The laser scanning procedure has been documented in the thesis of Sumantra Bagchi. *The Digital Reflection: Implications of Three Dimensional Laser Scanning Technology on Historic Architectural Documentation.* 2001, Master Thesis, Texas Tech University.

[4] HABS architects, Dana Lockett and Mark Schara worked with TTU on the initial survey of targets. The known sway of statue is 7.62cm (2.9999 inches) in a 50 mph wind while the torch sways 12.7 cm. (5 inches) at that wind speed. http://www.endex.com/gf/buildings/liberty/libertyfacts.htm, pg 2. Accessed January 1, 2002.

[5] Jared Wright, a graduate student and Jon Gamel, an undergraduate student were the research assistants on the Digital Liberty project.

[6] New computers that are now installed have a 3DLabs WildcatIV VP870 Graphics card with 3G of random access memory (RAM) on a Dual Athalon motherboard in the central processing unit (CPU). January 2003.

[7] The research assistants have kept logs of their work that can be viewed online. The Digital Liberty website can be accessed at www.arch.ttu.edu/Digital__Liberty/for more information about the process of data conversion and manipulation.

[8] Geomagic Studio freezes before completing the tessellation process. A myriad of technical difficulties beset the data-conversion primarily caused by the enormous amount of data, approximately 98 million measurements, excluding the high resolution scans of the head and torch. The computers freeze and require rebooting to continue work. Even segmenting the information into reasonable portions causes sluggish movement of the point clouds.

[9] The Digital Michelangelo is a joint project of Stanford University and the University of Washington. The team spent the 1998-99 academic year in Italy scanning the sculptures and architecture of Michelangelo. Roberto Scopigno at the Istituto Scienza e Tecnologie dell'Informazione (ISTI-CNR) have produced high-resolution images of many of the statues, utilizing the scan data. http://graphics.stanford.firenz.it/projects/mich. Accessed December 29, 2001.