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Measurement of the U.S.S. *Monitor* Propeller Using Structured Light and Coherent Laser Radar Scanning Technologies

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ABSTRACT

*This presentation and technical paper describes the scanning and processing of data for the recovered propeller of the United States Navy Warship **U.S.S. Monitor.** The propeller, designed by inventor John Ericsson, was recovered by NOAA in 1998, conserved over the next six years, and is now on display at The Mariners' Museum in Newport News, Virginia, where it was scanned in place. Two different measurement technologies were employed to meet the goal of high accuracy and high resolution. The Coherent Laser Radar system was used to scan the overall propeller surfaces at a resolution of 3 millimeters. A Structured Light Scanner was then employed to scan at resolutions down to 12 microns to capture details such as surface features and graffiti etched on one of the blades. The point clouds were then merged to generate an accurate model for dimensional and hydrodynamic analysis. This presentation provides detail and highlights of the scanning and data analysis activity.*

INTRODUCTION

History of USS *Monitor*

April of 1861 marked the beginning of the American Civil War. The North devised the Anaconda plan in which they would blockade more than 3500 miles of coastline from Virginia to Mexico and up the Mississippi river in order to restrict rebel commerce with Europe. This made it all too clear that the outcome of the war would be heavily dependent on the naval resources each side could muster.

For both the North and the South, one of the most important coastal regions was Hampton Roads, where the James River met the Chesapeake Bay. For the North, the James River was the passageway to Richmond, the capitol of the Confederacy. For the South it was the passage to the sea and potential European allies.

During the Civil War, the most advanced and powerful naval warfare vessels were brought to engage in the struggle over control of Hampton Roads. While the South was retrofitting the captured USS *Merrimack* in Hampton Roads with iron armor, the Union Navy turned to constructing a radically different ship, the USS *Monitor*. John Ericsson, a Swedish-American naval engineer and designer of the *Monitor*, employed a truly innovative design for the ship that included a revolving gun turret, complete iron construction, and a screw propeller. See Figure 1.

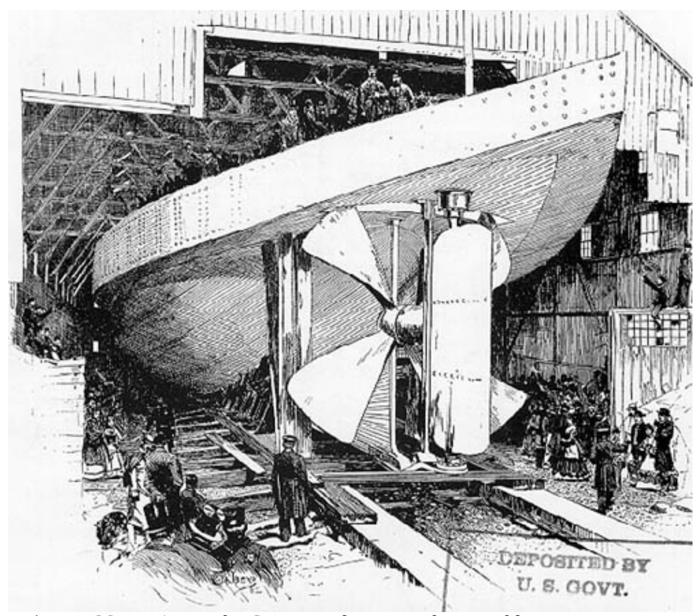


Fig. 1 USS *Monitor* at the Continental Iron Works, Brooklyn, NY

Ericsson and his partners were given 100 days to build his state-of-the-art warship, which was to face the South's 'indestructible' retrofitted *Merrimack*, rechristened the CSS *Virginia*. After a successful launch and sea trials in New York, the *Monitor* steamed to Hampton Roads. On March 9, 1862, the *Monitor* reached its destination and engaged in its famous battle with the *Virginia*, which symbolically marked the end of the age of wooden war vessels. Although the battle was a draw, the *Virginia* was scuttled by the Confederates two months later to prevent capture by the encroaching Union Navy. The *Monitor* then reigned supreme over Hampton Roads during the summer of 1862.

In the fall of 1862, the *Monitor* made a brief visit to the Washington Navy Yard for routine maintenance. On Christmas Eve of the same year, the *Monitor*'s crew was ordered to take the ship, under the tow of the USS *Rhode Island*, to Beaufort, South Carolina. On New Years Eve 1862, while on its way to Beaufort the ship sank in a fierce storm off the coast of North Carolina. Many of the officers and crew were rescued by lifeboats from the *Rhode Island*, but despite these efforts, 18 sailors were lost that night.

Archaeology and Conservation

After resting undetected on the ocean floor for 111 years, the wreck of the USS *Monitor* was located by a team of scientists in 1973. The remains of the ship were found 16 miles off Cape Hatteras, North Carolina at a depth of 240 feet. The *Monitor*'s hull was lying upside down on top of the gun turret.

To protect the remains of the ship, the site was designated the nation's first cultural marine sanctuary in 1975. The *Monitor* National Marine Sanctuary is managed by the National Oceanic and Atmospheric Administration (NOAA).

NOAA, working with the US Navy and other partners, has conducted numerous research expeditions to the wreck site. After observing significant deterioration at the site in recent years, NOAA developed a long-range stabilization and recovery program for the wreck. As a result, thousands of artifacts including the turret, steam engine, and propeller, have been recovered and transported to The Mariners' Museum in Newport News, Virginia for conservation, storage and display within the past decade.

The conservation of the recovered artifacts is now the largest project of its kind in the world, with over 250 tons of artifacts to preserve and document. The Mariners' Museum conservation team and NOAA are developing and utilizing state-of-the art technology to accomplish these tasks.

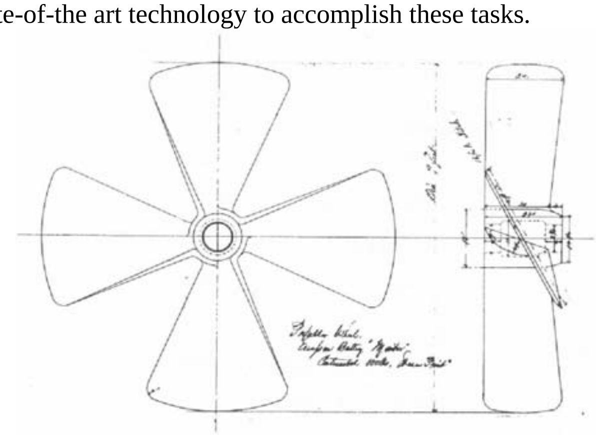


Fig. 2 Propeller Drawing Dated Circa. 1861

Propeller Specifications

Most ship designers in the early nineteenth century were aware of the principles of Archimedes screw and were testing various types of screw designs for steam driven ships.[i] One of these designers was John Ericsson, the first to patent the screw propeller in America.[ii] The four-bladed cast iron propeller on the *Monitor* represents the success of his design (Figure 2).

The propeller of the USS *Monitor*, along with its steam engine, was manufactured by Delamater Iron Works in New York City (Figure 3).[iii] Delamater was reputed to be the largest steam-engine manufacturing establishment in the country at that time.[iv]

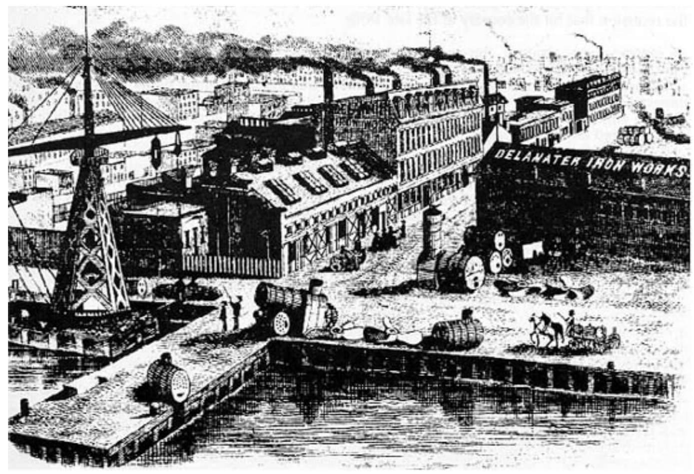


Fig. 3 Delanater Iron Works where the USS *Monitor's* propeller was cast.

In most accounts, the propeller was detailed to measure nine feet in diameter with a sixteen-foot pitch.[v] Archaeological recovery of the propeller in 1998 revealed that large portions of three of the blades were absent. Conservation treatment revealed distinct break edges along the missing areas. It is not certain whether the propeller broke during sinking or during operation, as there are no historic accounts of the latter.

Detailed laser scanning of the surface has provided a greater insight into the specifications and accuracy of manufacturing of the propeller. The 3D model generated from the point cloud data will allow for additional analysis in both the manufacture's tolerance capability and the hydrodynamic characteristics of the propeller. Finally, the 3D model will serve as a record for conservators to refer to when assessing the artifact for active deterioration.

Nomenclature

The following terms and acronyms are used in the subsequent sections. Additional descriptions and details may also be found in the endnotes of this paper.

Accuracy – In general, the term has been misused to the point that the word is diluted. Specifically, this writing uses the word to mean the uncertainty of any measurement technology.

GD&T – Geometric Dimensioning and Tolerancing referenced as the ASME 14.5M –00 Standard.

Point Cloud – A group of points contained in a single file with a standard or proprietary format.

Uncertainty – The statistical development of multiple measurements stated as standard deviation (one Sigma), two or three Sigma depending on project requirements.

Structured Light Scanner – Also known as a "fringe projection system" or "white light scanner" uses the principle of triangulation for determining range to an object.

SCANNING TECHNOLOGIES EMPLOYED

The first method of measurement for the USS *Monitor* Propeller was by means of Coherent Laser Radar (CLR). This was done in the museum with no alteration of the exhibit's armatures required. The measurements were taken by moving the instrument around the artifact to access as much of the blade and hub surfaces possible. Some areas were not accessible by direct scanning. Although reflective means was available, it was considered faster to "touch up" these areas using Structured Light, or triangulation scanning technology.

The structured light scanner was used to measure surface deviations in detail. This allowed the recording of fissures, cracks and an area with historic graffiti found on one of the propeller blade tips. The structured light point clouds provided a great amount of detail and were easily aligned and merged with the accurately measured model generated by the CLR scanner. See figure 4.

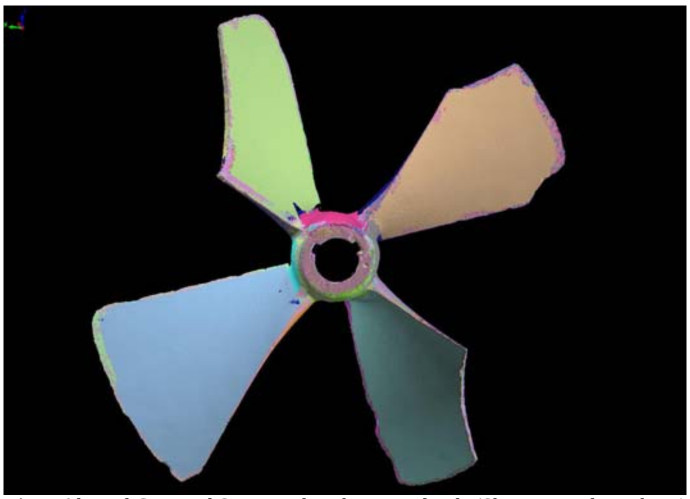


Fig. 4 Aligned CLR and Structured Light point clouds (Shown in Polyworks™)

A review of these two technologies is discussed in the following sections. Note that each has specific strengths and weaknesses and applications determine the selection.

CLR Technology

CLR technology[vi] uses the concept of coherent wave technology applied to the frequency modulation (FM) of an infrared laser. It is bundled into a system with vertical and horizontal axis servos, digital focus for the infrared beam, a red pointing laser for locating beam position and a video camera with cross-hairs for the operators' control panel. For coherent, or FM laser radar, the frequency of the laser is modulated with a saw-tooth wave, resulting in linear modulation. This type of modulation is often referred to as a chirp. Figure 5 depicts this scenario. A portion of the transmitted infrared-chirped beam is split from the incident light wave. This forms the local oscillator, which is then mixed with the returned reflected energy to measure the range of the object.

In early FM devices, the accuracy of range measurement was limited by the linearity of the frequency modulation over the counting interval. For example, if the target is one meter distant, a linearity of one part per thousand is necessary to ensure 1 mm accuracy. Advanced techniques employed in the CLR enable a high degree of linearity. In addition, these techniques can detect and compensate for real time variances from linearity. This enables range measurement with single digit micron precision.

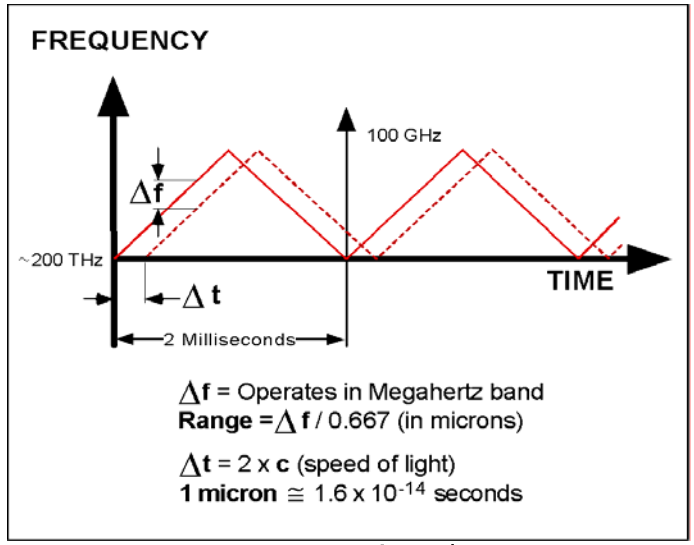


Fig. 5 FM saw-tooth wave form

FM lasers are largely immune to ambient lighting conditions and changes in surface reflectivity because FM laser radars rely only on beat frequency, which is not dependent upon signal amplitude, to calculate range. This enables the FM Coherent system to make reliable measurements with as little as one Pico-watt of returned laser energy. This corresponds to a nine order-of-magnitude dynamic range of sensitivity.

A considered limitation to CLR technology is the requirement that the laser be a focused beam. Much like a camera, the operator must plan and work within a range-based focal length and measurement cannot be taken outside of these limits. However, since the beam is focused, it can be reflected from a mirror and projected onto a hidden surface. With an algorithm, an optically flat mirror can be positioned and used to measure surfaces that are out of the line of sight of the instrument. This is a great feature of this technology allowing measurement of in-accessible surfaces.

The operating system is PC based software with an incorporated UPS back up built into the field equipment. The system performs single point-to-point measurements, similar to a laser tracker, but also incorporates the ability to scan surfaces reflector-less far more accurately than other laser systems. Since both features are incorporated into the CLR system software, is it capable of statistical quality data for each point measurement.

This technology is applicable for the measurement of the USS *Monitor* propeller since it provides high accuracy data with the ability to point measure to maintain coordinate system relationships with each instrument position. See Figure 6. This means the instrument can be moved around the perimeter of the artifact (the propeller in this case) and continually measure data within the coordinate values common to the project. An example of this is shown in Figure 6 where all instrument locations as shown in relationship to the exhibit.

Fig. 6 CLR scanner behind propeller exhibit.

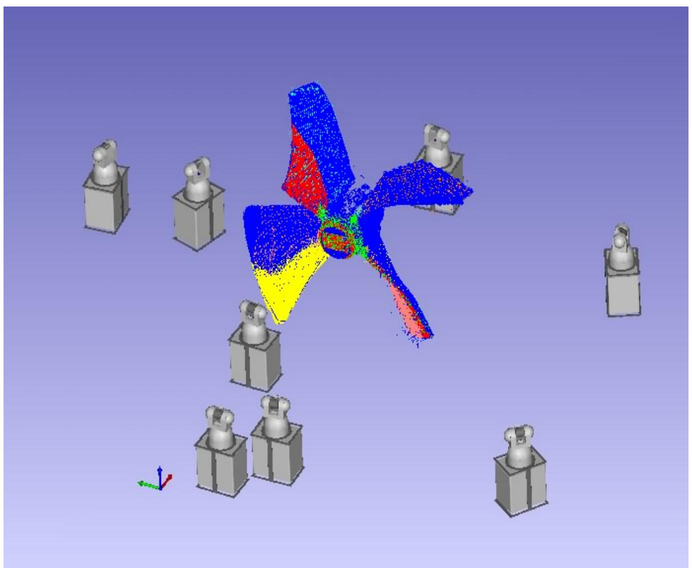


Fig. 7 Instrument arrangement during propeller scans.

Structured Light or Triangulation Scanning Technology

This method projects patterns of light (grids, stripes, elliptical patterns, etc.) onto the subject surface by means of a grating built into a projector, which uses a halogen light source. The projector is mounted on one end of a composite bar. On the other end is a digital camera set to a corresponding focal depth referenced to the bar length. The feature sets the operating "field of view" for the measured area, which determines the area observed in each scan, and the resulting resolution of the scan data. See Figure 8.

Distinct fringe patterns that appear as dark and light stripes are captured by the digital camera and used to compute the surface shape and topography of the object. Surface topological features are deduced from the distortions of the patterns that are produced on the measured surface as shown in the example in Figure 9.

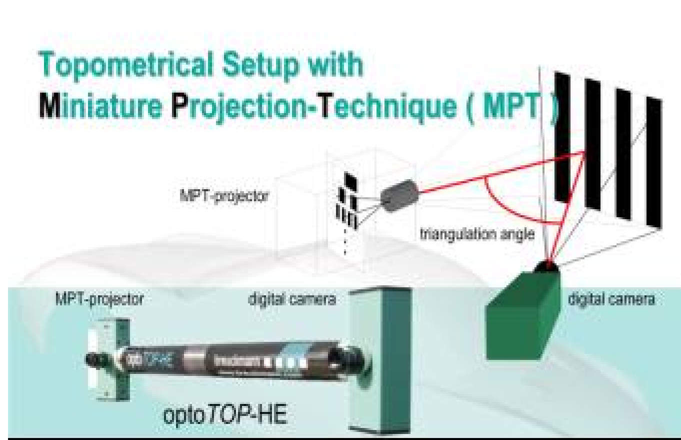


Fig. 8 Structured Light (triangulation) technique.

The scanner used for the USS *Monitor* uses a proprietary technique, known as miniature projection technique (MPT)[vii] which projects the fringe patterns in rapid sequence. The digital camera records these images and processes them by a combined Gray Code/Phase shift technique to compute a dense cloud of three-dimensional coordinates for the surface of the part being measured. The entire sequence takes a few seconds to complete.

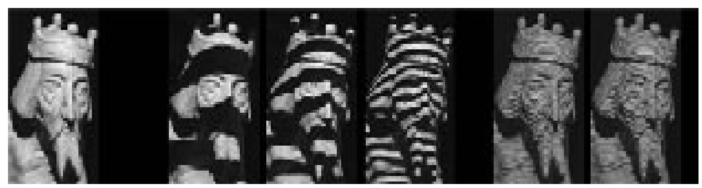


Fig. 9 Patterns during scanning projection sequence.

Each scan will capture over one million points. The scans are overlapped to capture data from multiple views, making it possible to capture all sides of a three dimensional object. Figure 10 shows the initial point cloud data from the blade surface after the first five scans were taken.

This process is continued until the entire area of interest has been scanned. The data consists of a cloud of points, which can be analyzed and processed in the same manner as has been described in the section on the CLR scanner.

An example of the entire back surface of the blade is shown in Figure 11. All of the individual scans have been aligned to produce a high-resolution point cloud. The high degree of contour and irregularities in the surface made it possible to align these scans without the use of any external system. In cases where the surface is very uniform, the scans can be aligned to a grid of known coordinate positions.

It is common to use photogrammetric techniques to establish a network of known coordinate locations. These typically are adhesive targets that are also recognized by the structured light system and used to align the scans. However, in this project, the combination of surface geometry plus the overall dimensional control from the highly accurate CLR scans was sufficient to locate the scans from the Structured Light system in the overall coordinate system.

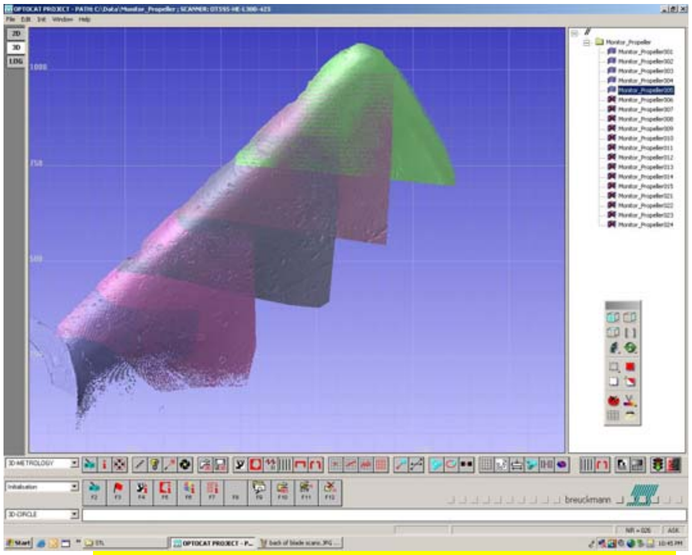


Fig. 10 Series of initial scans from the MPT scanner showing overlap areas.

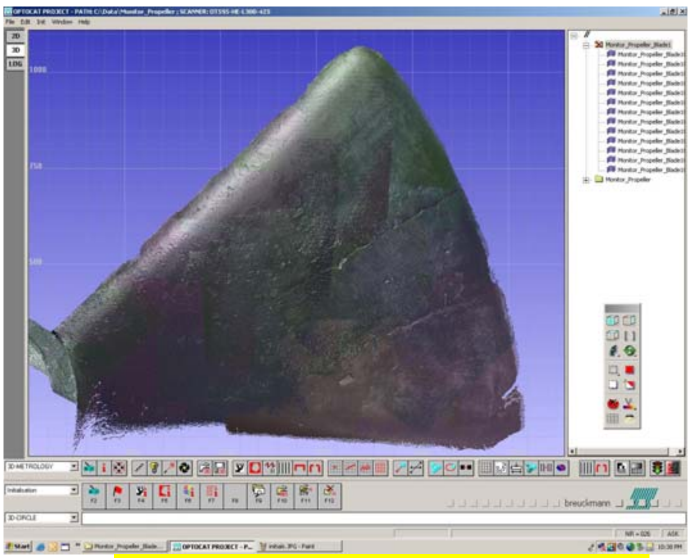


Fig. 11 MPT scan data from showing surface contour and topography.

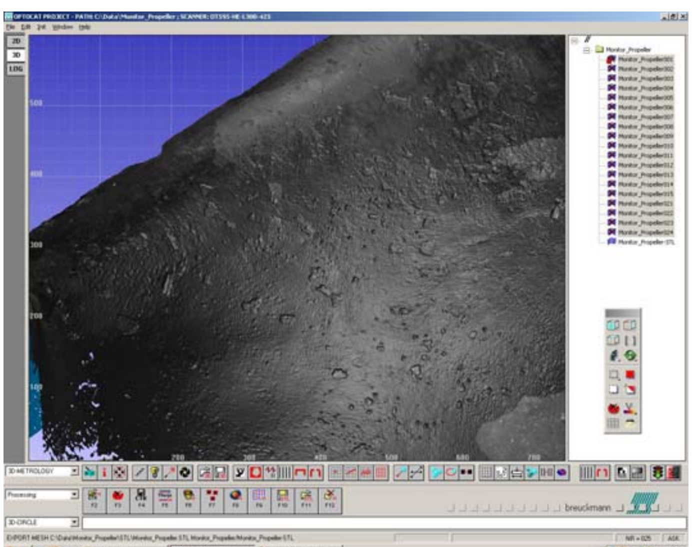


Fig. 12 The high resolution Structured Light scan data clearly shows pitting and deterioration in the blade surface.

A close-up of a portion of the blade in Figure 12 shows the high level of detail that is obtained with the Miniature Projection Technique (MPT) system. The pits in the surface of the propeller blade are the result of corrosion and can be clearly seen.

In this project, the structured light scanning system was used with a portable tripod. This provided a flexible mounting arrangement that made it possible to obtain data in difficult areas. Figure 13 shows data collection on the underside of the lower propeller blade. In other applications, the scanner might be combined with a rotary table or mounted on a robot. However, the tripod mount enabled the collection of data in areas very close to the floor.

Fig. 13 Structured Light scanner being used on underside of Blade #3.

Both technologies bring a high degree of accuracy to any project, and both have significant use for antiquities such as the propeller. The CLR scanner will provide a large accurate model of the artifact with a 3-millimeter density scan. The scanner can provide greater resolution[viii] but the time allotted to complete the scanning activity restricted higher point cloud densities. For this reason and the considerations of temperature changes and vibrations, the structured light scanners were used to achieve greater resolution while production faster point acquisition times. Combining the two systems provided a flexible and efficient means of collecting the desired data.

Execution of CLR Measurements

The CLR scanning activity was performed by locating the scanner around the exhibit. The results are quantified below:

Duration of Scan Time:	36 hours
Number of Perimeter Scans:	55 Point Clouds
Number of Instrument Locations:	9 Positions
Total Number of Points:	1,667,984 points

Prior to the scan, a control network was installed. This network consisted of ½" diameter tooling balls mounted in magnetic drift nests and temporally fixed around the exhibit. Each tooling ball was designated as a Control Network Monument (CNM). CNM locations were chosen to assure that a minimum of six (6) tooling balls would be available for measurement from any instrument location around the propeller. The CNM measurements were then transformed into the working coordinate frame in order to value scanned point cloud data. The uncertainty of these point clouds can then be referenced to the CNM values generated at each instrument location when transforming into the network. The uncertainty is then calculated using the Unified Spatial Measurement Network™ available on the Spatial Analyzer operating system.[ix]

Execution of MPT Scanner Measurements

The Structured Light scanning activity was also performed by locating the scanner around the exhibit. The results are quantified below:

Duration of Scan Time:	4 hours
Number of Perimeter Scans:	33 Point Clouds
Number of Instrument Locations:	33 Positions
Total Number of Points:	17,125,371 points

This scanning was performed without reference points or targets. The scanned surfaces exhibited adequate topography to allow best-fit parameters to achieve accurate positioning within the software. As point clouds were completed and assembled in the software, features of the propeller such as hub and blade surfaces were easily recognizable for inclusion into the CLR point cloud data. The high resolution MPT scanning technology supplemented the courser grained CLR scanning to provide a detailed large-scale point cloud.

Processing of Point Cloud Data

Point Clouds from both MPT and CLR scanners were aligned and processed using a surfacing-software[x] capable of accepting ASCII (*.txt) formatted data. See Figure 10. Each point cloud was then aligned and meshed to a tolerance that strives to equalize the polygonal leg lengths. This reduced file size and was used to achieve smoothing effects in the model processing. See Figure 14.

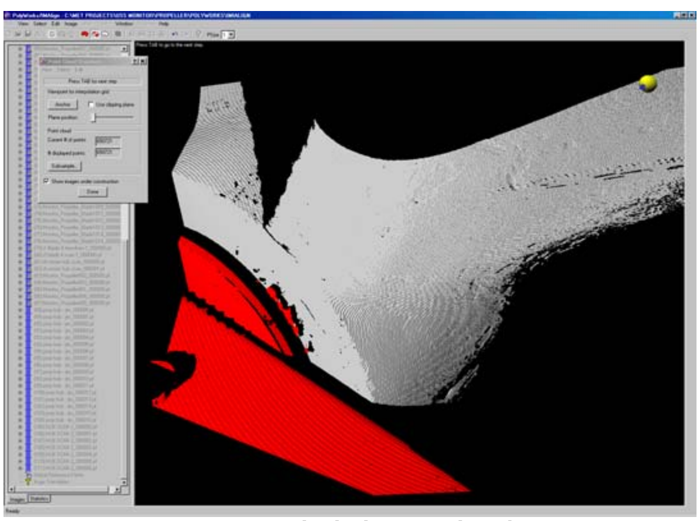


Fig. 14 Point Cloud Editing in Polyworks

When the alignment of the point clouds was complete, the meshed surfaces were merged into a polygon model. After generating the polygonized model the data was employed in three distinct ways. The first was the surfaced point cloud which was an as-built representation of the measurement. This form serves as an un-edited 3D model for comparisons, dimensional take-off's and GD&T purposes. It also provides an archival record, which captures detailed information about the current condition of the object including evidence of change or other damage. The polygonized model was also used to generate an edited 3D model where holes in the scanned data were filled and surfaces smoothed to a nominal extent. This is known as reverse engineering where a "water-tight" model can be used for photo-realistic imaging, 3D printing and animation. The third use of the scan data was the generation of a 3D CAD model where the measurement data was used to generate a theoretically perfect model. In this mode, the as-built data is converted to primitive and freeform surfaces.

As-Built Model and Analysis

The propeller scan data, in ASCII point cloud format, was merged into surfaces using either point coordinates as the vertex of each polygon or a mesh routine found in some software to equalize polygon leg lengths. As described earlier, each point cloud can be aligned using "best-fit" algorithms. Another method is to value the measured points while scanning. This is usually achieved by transforming instrument locations into common control networks or by using registration target points installed with a secondary measurement system that can measure discrete targets.

For the USS *Monitor* propeller data, point cloud data taken with the CLR scanner was measured within the reference coordinate system established by the Control Network. This allowed the generation of a 3D model using quantified point cloud uncertainties directly related to the location uncertainty of each instrument. This advantage allows each point cloud a quantified uncertainty.

Once this 3D model is generated, it can be used for dimensional analysis, GD&T, and color comparison to 3D CAD or other 3D as-build models. Figure 15 shows the comparison of the propeller as-built 3D model to a generated 3D parasolid model. The parasolid model provides a reference. This is explained in detail in a preceding section.

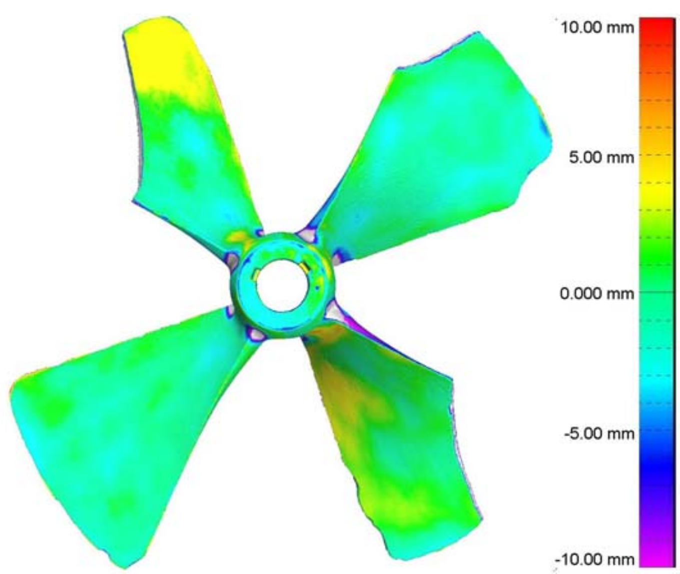


Fig. 15 Color comparison chart of as-built model to parasolid model

Reverse Engineering of the Propeller

The second method of processing scanned data is commonly referred to as reverse engineering. This is the process of modeling the as-built data and adjusting the output to fill holes, correct curvatures and smooth surfaces. Although this is not acceptable as inspection data, it does provide a critical function in the replication market. The USS *Monitor* propeller will be replicated many times using the processed data from this scanning activity; therefore, it is the modeler's responsibility to replicate the features of the propeller to the greatest degree of accuracy.

The process of editing point clouds is labor intensive and does require knowledge of how the data was taken. This allows for intelligent decisions regarding hole filling and smoothing routines that will produce the most accurate renderings of the part. The CLR scanning of the propeller consisted of 85% of the total surface area. The MPT scanning covered another 12%. This left an estimated 3% of surfaces to construct, not including the propeller bore which was generated from original drawings[v] and incorporated into the model. The result was a "watertight" three-dimensional model. See Figure 17.

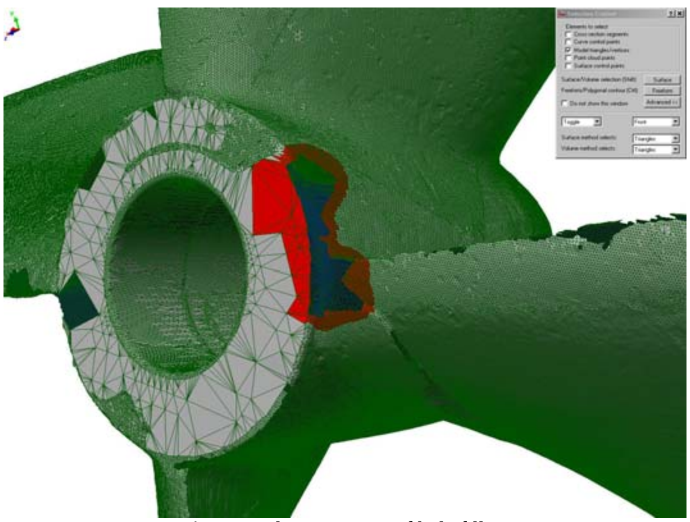


Fig. 17. Editing process of hole filling

Generation of a 3D CAD Model

A Non-Uniform Rational B-Spline (NURB) surface model, or 3D CAD model, was generated from the scan data. The CAD model will be used for two main applications. It will be utilized to produce a replica that does not include the damage that the original propeller has sustained. Hydrodynamic analysis will also be performed using the CAD model.

A couple of methods were utilized to generate a CAD model from measurement data. Primitive features, such as planar and cylindrical surfaces, were created using a best-fit routine. A region of measured points was selected, and the software used an algorithm to fit a primitive surface to those points. Complex surfaces were created by using freeform routines, which loft surfaces through 3D curves.

Cross-sections curves were generated from the measurement data. These cross-sections included the existing damage and imperfections, so a smooth curve, or spline was carefully fit to each cross-section. Cross-sections and surfaces were created from the intact propeller blade. See Figure 18. The surfaces were then extended beyond the damaged edges of the propeller blade.

Each freeform surface was inspected using a series of face analysis tools to ensure it was smooth and continuous and that it did not contain and spikes or self-intersections. See Figure 19.

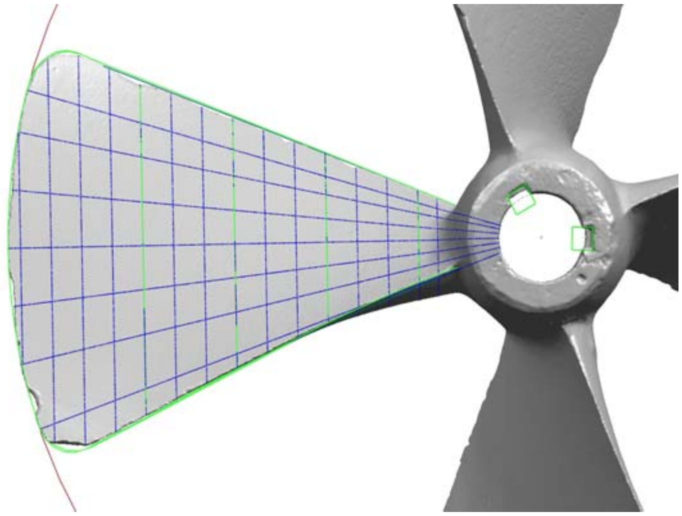


Fig. 18 Cross-section curves

Once each surface was modeled, it was trimmed and attached to its adjacent surfaces resulting in a solid 3D model. The propeller blade was instanced at 90º and united with the model of the hub, and blend features were applied where required.

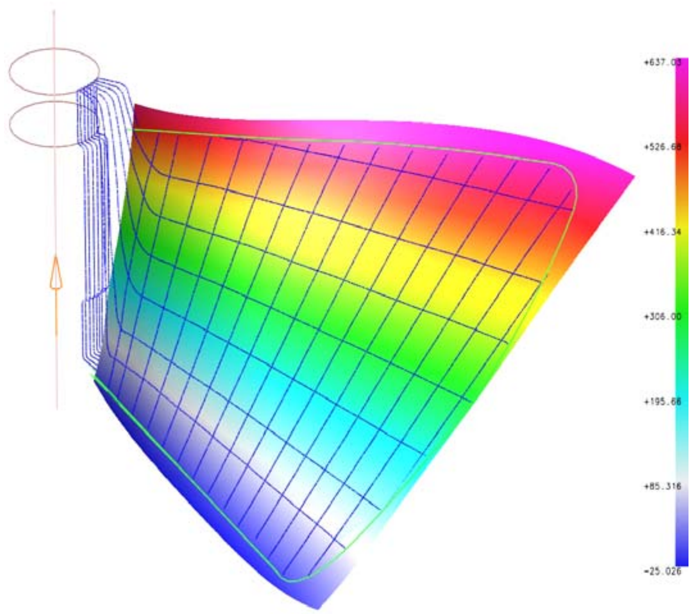


Fig. 19 Face analysis of propeller surface

The final CAD model can be read into most Finite Element Analysis (FEA), Computer Aided Manufacturing (CAM), and drafting software packages. See Figure 20.

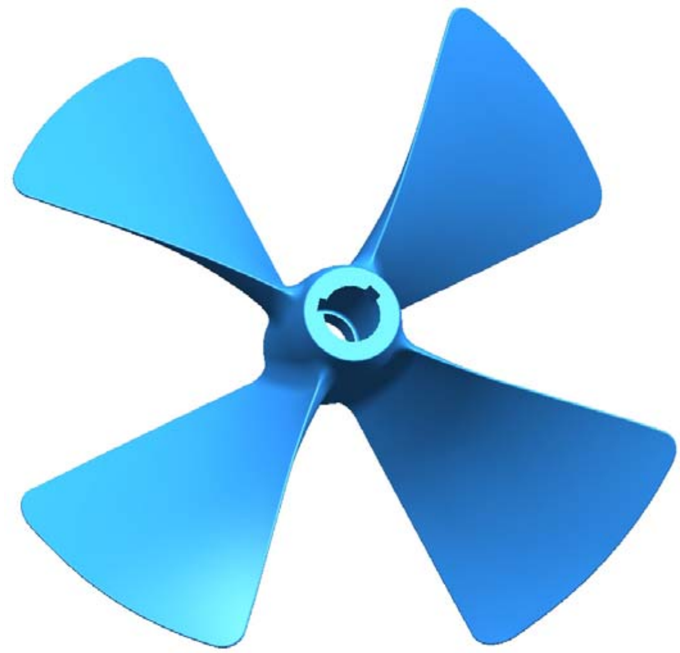


Fig. 20 3D parasolid CAD model

CONCLUSIONS

Manufacture Tolerances of the Nineteenth Century

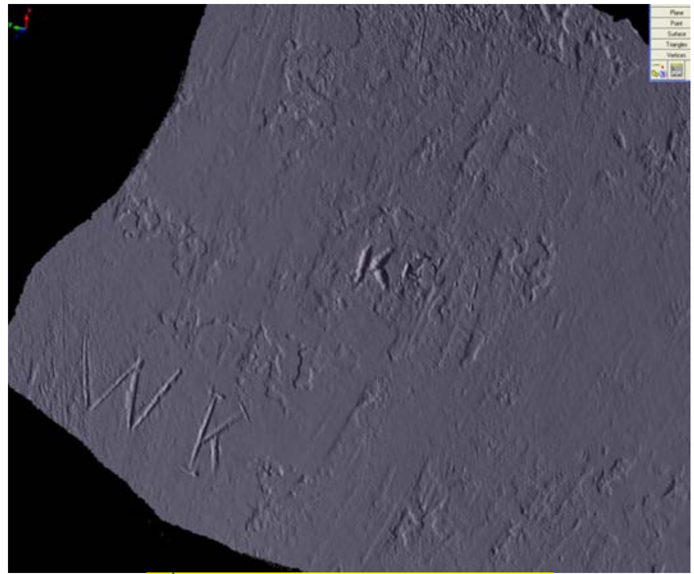
The measurement and processing work performed provides an insight into the results of manufacturing of the early 1860's. It is possible to see that Ericsson's propeller is within a probable tolerance of ± 10mm [0.38 in]. With the speed of the ship's fabrication and the limits set by the designer, it is notable that this would be an acceptable tolerance even in today's standards. See Figure 14 for Dimensional Color Comparison.

Multiple Scanning Technology Interface

This project validates two critical principles in the metrology industry. The first is the potential benefit of using multiple systems to achieve an optimal result. This is made possible by the introduction of common cloud point file formats. The best of each scanning technology can be incorporated to deliver both accuracy and resolution to large objects. The overlay of high-resolution structured light scans onto a CLR generated point cloud frame was successfully demonstrated in an innovative adaptation of this principle.

Uniqueness of Data Applications

As noted previously, the uses of scan data as an inspection medium; analysis tool and/or manufacturing process are well practiced in our industry. However, as markets broaden, parameters and processes must develop and standardize to meet the needs of our inexperienced customers. This project is a good example of how multiple technologies can serve the customer's interest by providing usable processed data for highly sensitive applications such as documenting and analyzing the USS *Monitor*'s propeller. This experience should be applied to the expanding antiquities market when selecting scanning technologies and processing procedures in the future with a mind on accuracy, resolution and cost.



19th Century Graffiti on the *Monitor*'s Propeller

ACKNOWLEDGEMENTS

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END NOTES:

[i] Kemp, Peter, The Oxford Companion to Ships and the Sea, Oxford University Press, 1976..

[ii] US Patent Number 588, Dated February 1, 1838.

[iii] Still, William Jr., *Monitor* Builders: A Historical Study of the Principle Firms and Individuals Involved in the Construction of the USS *Monito*r, Washington, D.C., Department of the Interior, 1988..

[iv] Baughman, James P., The Mallorys of Mystic., Middletown, Connecticut, 1972..

[v] Propeller Wheel/Ericsson Battery 'Monitor/Continental Works, Green Point," Thomas F. Rowland, Jr. Collection, Rendered, October 1861 (est.)

[vi] Leica LR-200 Coherent Laser Scanner, Leica Geosystems USA, Norcross, Georgia.

[vii] MPT is the patented Miniature Projection Technology system used in the Breuckmann Opto*TOP*-HE 3D-Digitization System. Breuckmann is represented by Accurex Measurement Systems, West Deptford, NJ.

[viii] The Leica LR-200 Scanner can scan to a resolution of 1 Micron however the limiting factor is laser spot size. Vibration over time is also a consideration when using the CLR for high resolution.

[ix] Spatial Analyzer® is an operating software for the CLR Scanner. It is available through New River Kinematics, Inc. of Williamsburg, Virginia.

Polyworks™ by Innovmetric, Quebec, Canada