APPLICATION OF 3D MODELING IN SHIP RECONSTRUCTION AND ANALYSIS: TOOLS AND TECHNIQUES

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ABSTRACT

Using different data capturing techniques (manual drawing, laser pen-aided drawing, *MicroScribe* and *FaroArm* drawing, adjustable 3D pin and cardboard models) the hull of a vessel is reconstructed for further manual and/or computerized analysis (*I-Ship* program). The application of 3D computerized modelling techniques has hitherto been used for visualization purposes only (*Rhinoceros* software). The application of 3D scanning coupled with the specific use of customized software (by PRISM) reveals the potential for analysis of symmetry in reconstructed hulls. This pilot study used a scaled hypothetical model of a partially preserved Viking Age vessel found in the Roskilde Fjord, Denmark. Through the symmetry analysis of the hull of this vessel we can 'rediscover' hidden design aspects of ‘eye-built’ hulls, identify technological assembly processes, and facilitate accurate reconstructions of scaled and full-sized models. The effectiveness of 3D scanning for data capture and analysis suggest its applicability in ship reconstruction and analysis.

INTRODUCTION

Ancient ships pose complex problems in all aspects of their research. Archaeological investigations of shipwrecks are conducted in stages, starting with data capture and ending with object display and/or reconstruction. Although much data capture is obtained through elaboration of 2D drawings, photographs, and manual measurements of 3D objects, idealized models are drafted with *AUTOCAD* or other drawing programs. Recent advances in computerized visualization have resulted in an ever-increasing use of 3D models for presentation of reconstructed or preserved objects. We summarize the advantages and limitations of data recording techniques used in marine and nautical archaeology, focusing on the potential of 3D scanning technology to capture, archive, and analyze accurate, detailed 3D geometric models of ship hulls.

The hull of a vessel may be reconstructed using different data capturing techniques (manual or laser pen-aided drawing, *MicroScribe* and *FaroArm* digitizing, and adjustable 3D pin and cardboard models) for further manual and/or computerized analysis (*I-Ship* program) or 3D visualization (*Rhinoceros* software). In this study, we used a scaled hypothetical model of a partially preserved Viking Age vessel (from Roskilde Fjord, Denmark, http://www.vikingeskibsmuseet.dk) and applied 3D scanning and customized software (developed for the *3DK* project (Shurmans et al. 2002) by PRISM, http://3DK.asu.edu) to examine the potential of symmetry analysis for reconstructed hulls. Through such analyses, we can rediscover hidden design aspects of 'eye-built' hulls, identify technological assembly processes, and facilitate accurate reconstructions of scaled and full-sized models. The effectiveness of 3D scanning for data capture and analysis supports its further use in ship reconstruction and analysis.

RECORDING TECHNOLOGY AND TECHNIQUES

Viking Age ship finds recovered from archaeological contexts are a major information source on shipbuilding and seafaring (Crumlin-Pedersen 1997), but the challenges of data collection increase the complexity of reconstructing the maritime past. Hulls are often only partially preserved and without major structural timbers such as stems and sternposts as the result of a deliberate action (dismantling) or of formation processes. Northern European ships from the first millennium AD are often found without accompanying artefacts, which make reconstruction of the ship's hull imperative. These ships were built by eye and 'rules-of-thumb' and have no surviving written documentation. In order to rediscover the shipbuilder's knowledge of that period, the researcher has to piece together the recovered ship timbers to best resemble its original shape. The technological process is assessed to rediscover the mental template(s) used as a blue print in shipbuilding (Indruszewski 2000). For this purpose, expert knowledge and accurate measurements of preserved timbers are vital for the reconstruction of complex 3D ship shapes. Thus, nautical archaeologists are involved in 3D modelling and reconstruction from the very beginning and by the nature of the objects of interest.

But to do this, each recovered ship timber has to be measured and drawn by edge tracing; each timber is laid horizontally under a clear Plexiglas plate positioned parallel with the surface; edges and all other features pertaining to use-wear, functionality, and material are drawn on clear film affixed to the plate. Although this method is reliable, it also contains some difficulties; superimposed edges in the same plane are difficult draw in 2D. Tracing irregular and deformed edges and shape-ends has proved to be tedious, requiring many hours of effort. The amount of information rendered on a surface, encompassed between four inter-related edges or surrounded by a contour line, is a representation of the visual perception of the draftsperson at the time of drawing.

In 1998, an improvement was made by attaching a permanent marker (used in free-hand tracing) at an angle to a laser-pen set perpendicular to the drawing plane. By moving both pens as a unit, the operator is able to simultaneously trace the edge or any other feature on the object and on clear film. The result was improved drawing accuracy obtained with less time and effort. The drawings are scanned, scaled down, and printed for building a 3D cardboard model, which facilitates the reconstruction of the hull itself, the relocation of each timber, and importantly, defines the sequence of the assembly process. Once finished, the model is used for recording the ship lines from which the final ship drawings are elaborated. These drawings constitute the template used in the construction of full-size replicas and scaled models utilized in the study of practical navigation, technological processes, and analysis of hull hydrodynamics. The analysis is carried out at present by utilizing a software package called *I-ship* and *NMF-ship*, designed to construct a 3D hull and calculate several parameters such as main and additional dimensions, hydrostatic data, and form coefficients.

The *MicroScribe* and *FaroArm* devices recently replaced the manual edge tracing method and are used to digitize various ship timbers and/or entirely preserved hulls. By dragging the *FaroArm* pointer on the digitizing surface instead of marking points at regular or random intervals, the operator can produce computerized feature lines with less time and effort (3 hours for the Kolding cog knee and 1.5 days for the Hjortspring vessel hull). These lines of individual ship timbers are assembled into a hull 3D view with *Rhinoceros* software. However, the data capture is the electronic version of the manual edge-tracing method and is dependent on the operator's perception of the artefact; subtle surface deformations or deviations in planar shape may be missed. Differences between a 3D computer model and a 3D cardboard model become obvious while assembling ship timbers into a hull. Electronic edge tracing methods can't be applied in special cases where hulls, such as the 10th-century AD Ladby graved vessel, have been totally decomposed and where the only remaining evidence is rivet imprints and stains. In this case, a 3D model made of movable pins was required to obtain the lines of an otherwise invisible ship shape.

The *Rhinoceros* program is problematic for the recording and documentation stage and as an end-process for 3D visualization. Attempts to tie *Rhinoceros* to *NMF-ship* that would result in visualizing the hull and completing calculations on it have been unsuccessful. The latest version of *Rhinoceros* has enhanced interface capabilities and can carry out some hydrostatic calculations; but these standard calculations are not appropriate for Viking Age vessels because of the way these ships were built. *Rhino* cannot calculate displacement for hulls with 'naked edges' (that is, clinker-built hulls with strakes that overlap each other) below the designed waterline (DWL). The issue is further complicated by the fact that these hulls were not always symmetrically built, thus posing more calculation stress for *Rhinoceros* and also *NMF-ship* software (Jensen 1999).

SCANNING THE SCALE MODEL SHIP

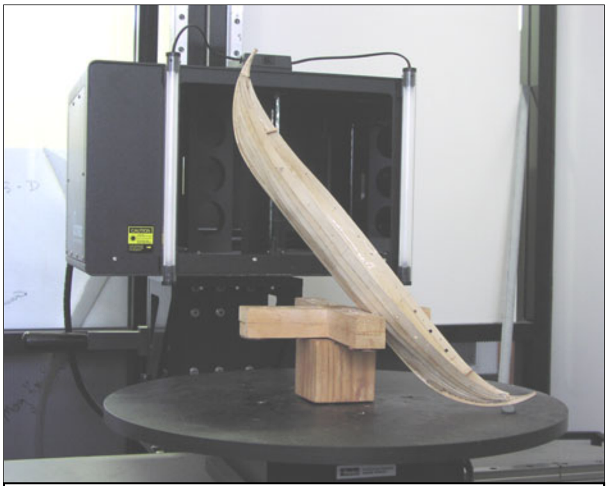

Figure 1. Scanning of the scale model Viking ship using a *Cyberware 3030 scanner* at ASU PRISM.

In 2002, the 3D laser scanning method was introduced (Figure 1) in an effort to document sequential working stages in the recording, analysis, and reconstruction of ship hulls. A scaled model of the *Skuldelev 3* replica, the *Roar Ege*, was built as a finite hull. Because the stern of the original sunken ship was not preserved, the dimensions and shape are approximated and mirrored. The scale model serves as a proxy and is used to assess hypothetical variations in symmetry of various sections of the ship and to examine how the shipbuilders made adjustments for the placement of the rudder on one side of the stern.

The ship model was scanned at the ASU PRISM lab (http://prism.asu.edu) with a *Cyberware 3030 Laser Scanner* (with RGB color) to capture three-dimensional geometry (Figure 1). The 3D model was built from a total of 48 scans (4 sets of 12 rotational scans) to capture the detail of the interior and exterior surfaces. The individual scans are merged to create one file.

The resulting coordinates (a 3D point cloud made up of individual x, y, and z coordinates) are fitted with a triangulated mesh using the *Cyberware* software. This produces a full-rotational 3D model of the object (Figure 2), not just the *appearance* of 3D obtained by animation of a series of 2D images (*QuickTime VR*). As in *Rhino* or *I-ship*, the 3D model may be rotated in all directions for close examination of features on the interior and exterior surfaces.

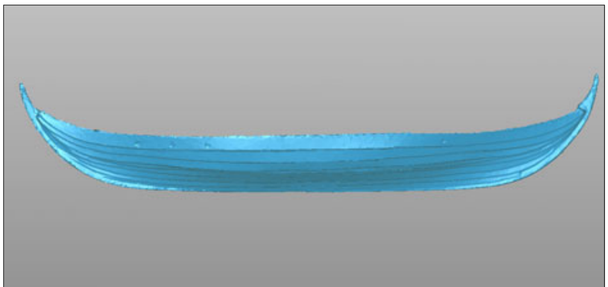

Figure 2. Side view of the 3D model of Viking ship scale model obtained from laser scanning.

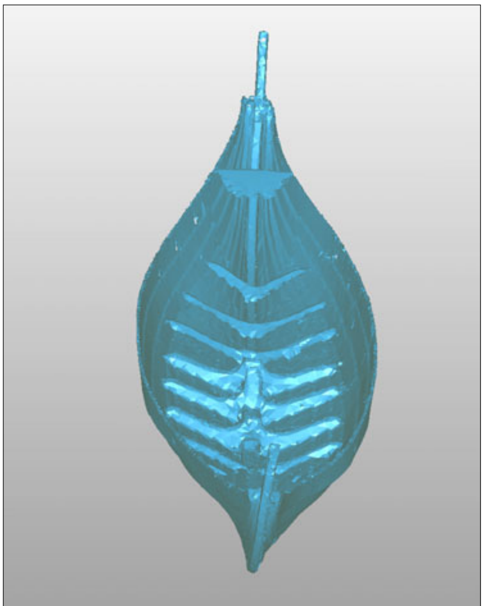

Figure 3. Oblique view of the 3D model of the Viking ship scale model.

An oblique view of the inside illustrates the internal structure of the hull (Figure 3) and the end view offers a profile of the ship and the hooding ends of the strakes (Figure 4).

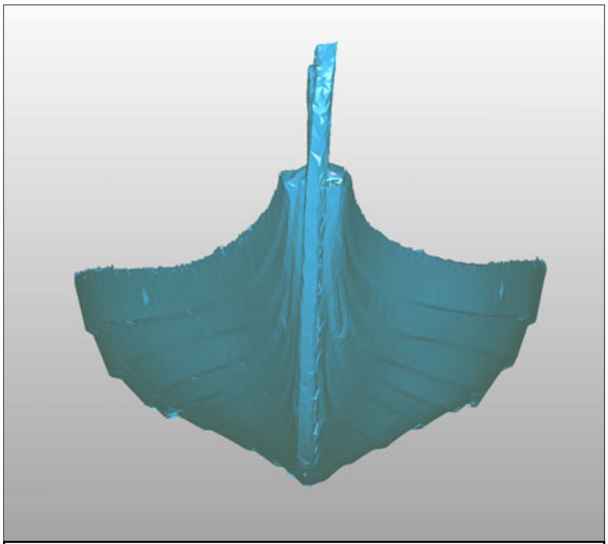

Figure 4. End view of the 3D model of the Viking ship scale model.

The 3D model file is reduced in size through a process called decimation (reducing the number of triangles to those essential to defining the object) to make it more manageable in the analysis software, but retaining the necessary data to define the 3D form in detail.

CURVATURE AND SYMMETRY

The methods used in this pilot study are drawn from those developed by PRISM (http://prism.asu.edu, http://3dk.asu.edu) for prehistoric ceramic vessels (Simon 1998, http://archaeology.asu.edu). As most ceramic vessels have a vertical axis of rotational symmetry, a *profile curve* is obtained by cutting a vertical cross-section through the vessel (Figure 5). The archaeologist controls the placement of three orthogonal planes to create a cutting plane best representing the profile of the vessel (Simon et al. 2002). The resulting string of points is fitted with a least squares cubic (degree 3) B Spline curve within a certain tolerance. The number of control points and the parameterization of the B Spline curve are automatically computed (Bae 1999) to smooth out the noise in the data and present the profile curve as a mathematical representation.

The *curvature plot* represents how the curve bends and flattens (Figure 5) (Farin 2001, Razdan and Farin 1998); given the curvature plot one can recreate the curve (barring position and rotation in space). Since the profile curve is a planar curve, its curvature plot is also two-dimensional; hence we can assign a sign to the curvature; i.e., positive or negative. Where the curvature plot crosses the zero line is called an *inflection*

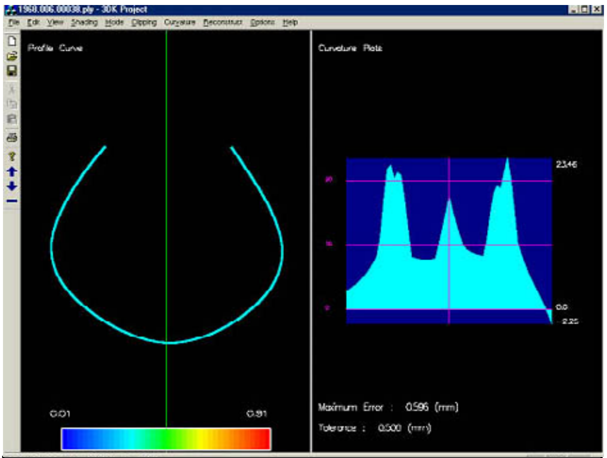

Figure 5. Ceramic analysis program developed by ASU PRISM, illustrating a vessel profile curve (left) and the corresponding curvature plot (right).

point, and these tell precisely where the curve changes from being convex to concave or vice versa. *Inflection points* and *corner points* (points of high curvature) are two important diagnostic features that are more easily detected from the curvature plot than the original curve.

Symmetry can be examined by mathematically comparing the two halves of the *curvature plot*. If the vessel is highly symmetrical, the two halves will not differ, but if the vessel is uneven, there will be considerable differences between the two. Symmetry is scored on a standardized scale (1 = high and 0 = low):

Let $f(x)$ be a (nonzero) function defined over $x \in [0,1]$. If f is symmetric with respect to $t = 1/2$, then $f(x) = f(1-x)$. A measurement σ for the symmetry of f is given by

$$\sigma f = \frac{\int_0^1 [f(x) - f(1-x)]^2 dx}{\int_0^1 [f(x) + f(1-x)]^2 dx} \qquad (1)$$

Further, a unit measurement σ' for the symmetry of f is defined by

$$\sigma' f = 1.0 - \sigma f \qquad (2)$$

Thus $\sigma' f = 1$ for a symmetric function.

Using this approach, the software developed by PRISM allows the quantification of the symmetry of 3D forms based on user-defined cross-sections. The symmetry measure is based on a difference in area between the two halves of a two-dimensional graph of the magnitude and direction of curvature (i.e., the curvature plot). This symmetry measure has been tested extensively on prehistoric pottery collections from Arizona and Mexico and yields interpretive results that are used in archaeological studies of ancient pottery technology.

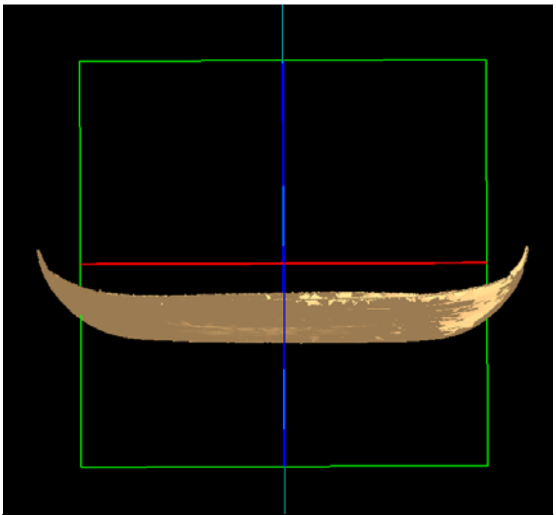

Figure 6. Side view of 3D model of the Viking ship scale model in the ceramic analysis software; the vertical blue line is the cutting plane for the symmetry analysis.

Although the ceramic analysis software has not yet been modified for objects with longitudinal (i.e., mirrored) symmetry, the user-defined sectioning with *profile curve* and *profile plot* can be successfully applied to the hull model example (Figure 6).

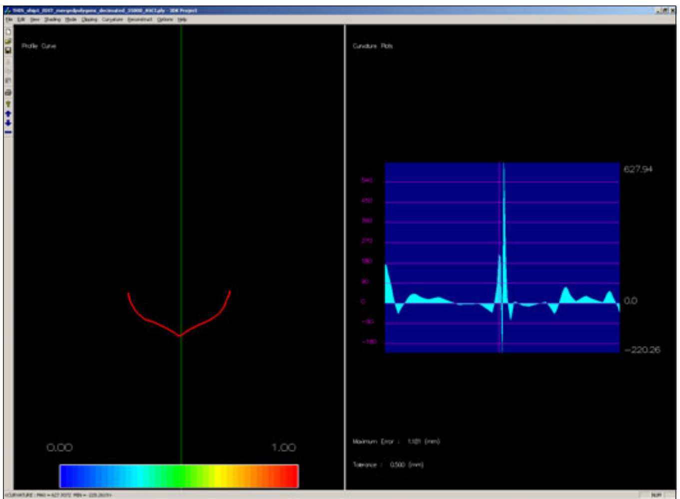

Figure 7. Analysis software view of mid-ship section illustrating profile curve (left) and curvature plot (right) of the scale model Viking ship; symmetry = .6204.

In this hypothetical case, we sampled cross-sections from the mid-ship, near the bow, and near the stern and these were evaluated against the two possible extremes (1 = symmetrical and, 0 = asymmetrical).

While we did not expect perfect symmetry due to cumulative variation from the individual strakes, it is informative to examine the variation in the scaled model as a proxy for full-sized ships. The section near the *bow* (Figure 7) is the most symmetrical (.7095), the *mid-ship* section (Figure 8) is slightly less symmetrical (.6204), whereas the section near the *stern* (Figure 9) has extremely low symmetry (.0467).

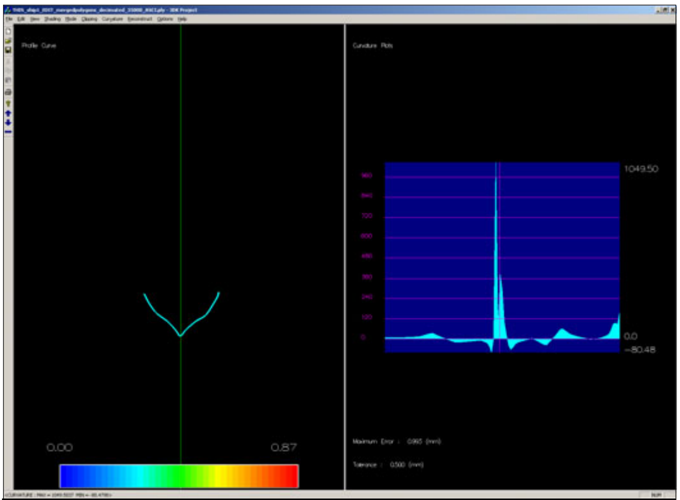

Figure 8. Analysis software view of a stern section illustrating profile curve (left) and curvature plot (right) of the scale model Viking ship; symmetry = .0467.

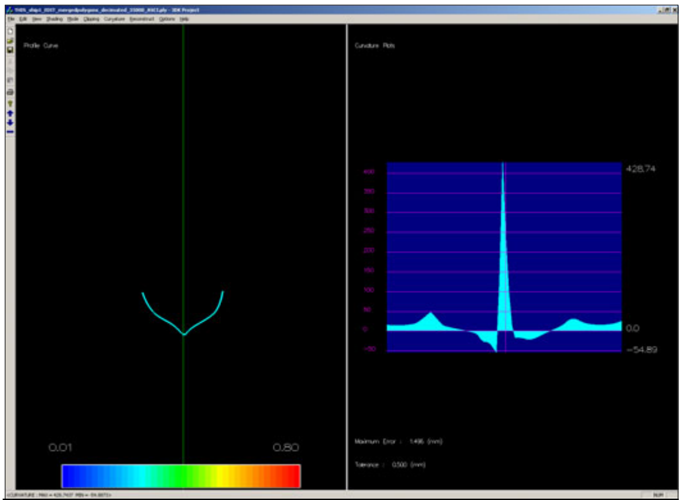

Figure 9. Analysis software view of a bow section illustrating profile curve (left) and curvature plot (right) of the scale model Viking ship; symmetry = .7095.

The resulting symmetry measures indicate that in a hypothetical scaled model of *Roar Ege*, the bow of the ship is the most symmetrical, whereas the stern is the least. If such asymmetry was documented in the actual archaeological specimens and was an intentional part of ship building technology, such asymmetry in the stern could potentially be related to the attachment and hydrodynamic role of the side-rudder against the hull. The challenge has been to obtain direct and accurate 3D data with which to quantify asymmetry to study such questions. Further research with 3D scanning of highly accurate reconstructions where the bow and stern are more completely preserved will be needed to fully test this hypothesis. However, this pilot study demonstrates the proof-of-concept that highly accurate scanning provided by 3D technology and customized analytical software has the potential to address these questions.

CONCLUSION

Access to 3D scanners, equipped to capture data on different size ranges of objects, is becoming more economically and technologically feasible for researchers in many disciplines. Recent advances in 3D scanning applications and CAGD modelling include the capturing of detailed and accurate point cloud data (x, y, and z coordinates), a surface texture map, and curvature modelling. With analysis using customized software, quantitative measures such as volume and symmetry can be obtained. A further benefit is the ability to make rapid prototypes of the scanned models at different sizes, for study and visualization. Although the current analysis software, designed for rotational symmetry, does not allow the generation of longitudinal profiles (buttock line sections) of the ship, PRISM researchers are developing software for the analysis of other types of symmetry.

Our experience with this pilot project indicates that the transformation and grouping of sequential working stages (from recording and documentation to display and analysis) from a manual to an essentially electronic process is far from complete. There are advantages to various methods, but there are still major issues to be addressed. For example, using a *FaroArm* to edge trace brings the documented ship timber closer to assembly, 3D display, and analysis, but a cardboard 3D model seems irreplaceable as a tool for understanding the assembly processes used in shipbuilding. However, the ultimate goal for 3D visualization is not display alone, but should include additional calculation capabilities that are sufficiently flexible to address specific problems arising from the nature of the artefact itself. Such interdisciplinary research expands the concepts and the means by which we learn more about 3D objects and the cultural and craft traditions that developed them.

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