

SURFACE SCANNING METHODS AND LARGE-SCALE FDM PRINTING FOR THE REPLICATION OF WATERCRAFT LAYUP TOOLING

D. W. Nuttall, A. M. Elliott, B. K. Post, L. J. Love

Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, Tennessee, 37830

This manuscript has been authored by UT-Battelle, LLC under Contract No. DE-AC05-00OR22725 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes. The Department of Energy will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (<http://energy.gov/downloads/doe-public-access-plan>).

ABSTRACT

The manufacturing of tooling for large, contoured surfaces for fiber-layup applications requires significant effort, with traditional methods for the auto industry using hand sculpted clay, and the marine pleasure-craft industry typically creating forms from foam lay-up, then hand cut or machined down from a billet. Oak Ridge National Lab's Manufacturing Demonstration Facility (ORNL MDF) collaborated with Magnum Venus Products to develop a process for reproducing legacy whitewater adventure craft via digital scanning and large scale 3-D Printing molds. The process entailed scanning a legacy canoe, converting to CAD, additively manufacturing the mold, and subtractively finishing the transfer surfaces. The outlined steps were performed on a specific canoe geometry, with intent to develop energy efficient, marketable processes for replicating complex shapes related to watercraft, and provide products for demonstration to the composites industry. It is anticipated that developing this process to manufacture tooling for complex contoured surfaces will have direct applicability to the sports/pleasure craft industry, naval and other watercraft, as well as bathrooms and large trucks.

INTRODUCTION

Additive manufacturing (AM) Fused Deposition Manufacturing (FDM) is a technique in which material is extruded into a pattern controlled by an x – y gantry, onto a z-height control bed. With large-scale printing, material in pellet form is delivered to the gantry mounted extruder where it then is heated and extruded via a compaction screw at rates between 70 and 100 pounds per hour. ORNL has optimized the process controlling shapes that span several feet in each direction to a tolerance of $\pm 0.050''$ using a 0.2 inch nozzle with acrylonitrile butadiene styrene (ABS) (80 vol%) / carbon fiber fill (20 vol%). This process combined with finishing techniques has proven to produce smooth lines as seen in the 3-D printed Shelby Cobra (2014) [1], the printed utility vehicle (PUV) (2015), and the Willys Jeep body (2015).

More important than printed vehicles, however, is that these large custom geometries with smooth contours are well-suited for fiber layup applications such and carbon fiber or fiber

glass molding. Because traditional mold-making for fiber layup is extremely labor intensive, expensive, and wasteful of material, the digital creation of layup tooling via large-scale FDM is a natural fit. A critical aspect of any AM process, however, is the digital design of the desired geometry. For legacy artifacts, 3D scanning can fulfill this need. This paper summarizes the work performed toward capturing the 3D shape of a large whitewater canoe via multiple surface scanning techniques.

BACKGROUND

MVP Marine is the leading manufacturer of a variety of equipment targeting composites applications. They serve customers in boat, bus, rail, truck, bathroom, bathtub, pipe, and other industrial or production applications.[2] As a feasibility study for the development of a process for molding watercraft geometries, a specific whitewater canoe tool modeled after the *Ocoee* design was selected for recreation. This design is built with the perfect ‘rocker’ positioned aft of center to allow the solo paddler maximum control in a canoe designed to handle streams and rivers with moderate rapids. This particular geometry not only contains subtle contours, but is enables the evaluation of scanning technology on large scale objects.



Figure 1: Canoe plug as received from MVP, in preparation for hand scanning.

Considering energy efficiency and time required to rejuvenate this particular canoe design, the plan was set to capture a digital scan of the plug and directly print the mold via large-scale FDM. This eliminated the time and energy costs of traditional pre-build methodology: (re)construction of the plug, fiberglass layup, and structural reinforcement. These steps typically take weeks to create a tool of this size. Surprisingly, however, the majority of this work focused on attempting to use various surface-scanning technologies to produce a useable digital pattern for printing.

METHODS

To initiate a printed design, one begins with a digital model in a stereo lithography (.stl) format, which may originate from a scan or a drawing via any number of computer aided design (CAD) software packages. The canoe plug provided by MVP was scanned using three different types of scanners: a low-cost *Sense* handheld scanner for moderate sized projects, a higher-end *GO!SCAN50* handheld scanner, and the high-end *FARO Laser Tracker* system. Scanning focused on the critical features of the canoe design, which includes the depth of gunnel, location of the rocker, location of max beam, and overall height (Figure 2). The usability of the digital scans provided by each scanning technique are discussed.

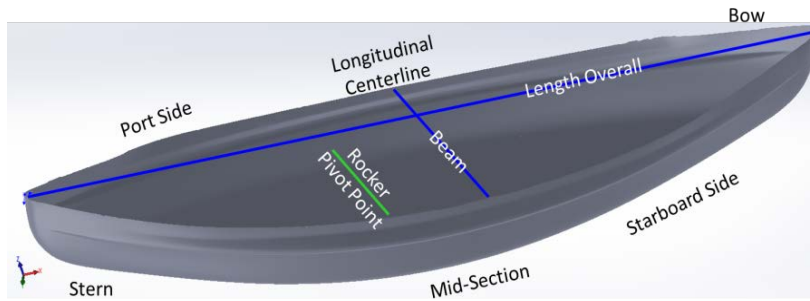


Figure 2: Canoe key definitions.

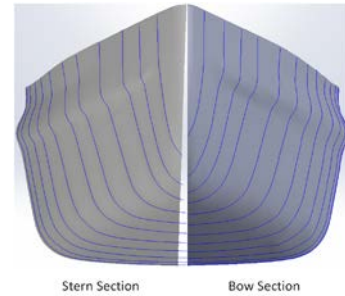


Figure 3: Hull lines.

The *Sense Handheld 3D Scanner* (Figure 4) was chosen as a low cost option to capture the canoe geometry as the advertised specifications seemed promising. However, a major discovery in using the *Sense Scanner* was the limitation in capturing the entire form. Although the specifications cite a scan volume of 2 x 2 x 2m [3], the software would truncate the surface data at 1m during the scan (Figure 5). Therefore, an attempt was made to scan the plug in three sections: bow, mid-section, and stern, with the intent to ‘stitch’ the scans together. This still proved unsuccessful due to the smoothness of the surface – there were no features for the scan to recognize as it progressed across the surface, limiting the data that was captured (e.g. incomplete fill). Many different lighting conditions, markers, and techniques for moving the scanner around the canoe surface were attempted. Overall, the *Sense* scanner fell short of the task of creating a complete surface scan.



Figure 4 Sense Hand Held 3D Scanner.

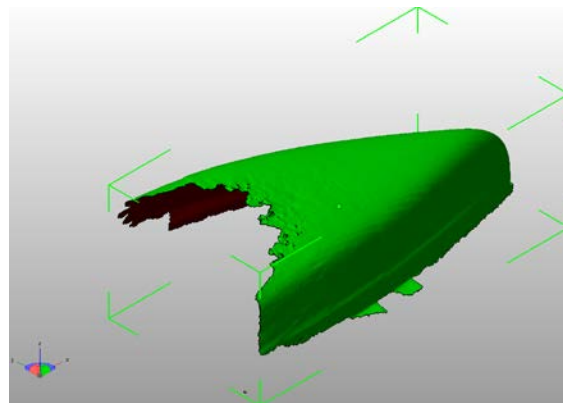


Figure 5 Resulting bow scan, incomplete data fill.

The second scanning attempt was completed by a contracted company, *Visionary Fabrication & 3D Design LLC*, who supplied services for scanning the canoe plug with a *Creaform Go!SCAN 50* unit (Figure 6). The accuracy of this unit is published as 0.5mm at 0.4m feature size [4]. Specialized treatment of the surface was required – placing markers on the surface in a random pattern allowed the vision system to track the surface more accurately. Extraordinary results in detail were obtained, however the dataset was too large to be processed on a normal PC. After multiple attempts at .STL refinement with *Geomagic Studio*, the dataset was manageable but the smoothness of the surface was lost. As seen in Figure 7, the

tessellations, or triangular shapes that the CAD program combines to define the surface or feature, are extremely dense and thus would cause the 3D printer to attempt to print multiple straight line segments the length of the legs of the triangles, and would not leave the actual features of smooth curves. Thus, although high resolution scanning was achievable, the average processor cannot handle the dataset.



Figure 6:
GO!SCAN50



Figure 7 Immense detail with tessellation structures in the shaded areas

It was not anticipated that, even though 3D scanning is simple to implement, the file sizes would be prohibitive for actual use in digital manufacturing. After investigating other options, the *FARO Laser Tracker* system located at the MDF seemed to be a viable solution. The technique used for the *FARO Laser Tracker* was to acquire the laser path with the spherical probe and trace the surface of the canoe, creating a series of data points or more specifically, contour lines. The *FARO Laser Tracker* method proved to be optimal, noting that the accuracy of this unit per the manufacturer's information [5] is 0.011mm at 20m.



Figure 8: FARO
laser



Figure 9: Laser tracker in use, tracing of the hull contour

Since the physics of plowing through, or in a canoe's case, over the water requires symmetry port to starboard, the approach was to trace the keel, the gunnel, and then model the port side from bow to stern. Spline lines approximately every 6 inches in highly detailed areas (e.g. bow and stern), and 12 inches through the midsection, connecting keel to gunnel, were traced and recorded. The captured data was then imported into CAD software (SolidWorks 2015) and the splines were merged progressively with the 'Add Loft Section' tool to form half of the shell. To complete the CAD form, the image was mirrored creating a complete shell representing the future structure. Figure 10 is a screen capture of an intermediate step illustrating splines to lofted panels, and Figure 11 illustrates the finished CAD canoe.

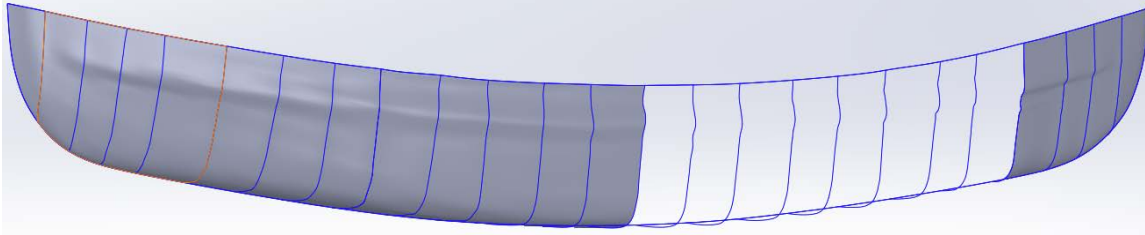


Figure 10 Splines and lofts.

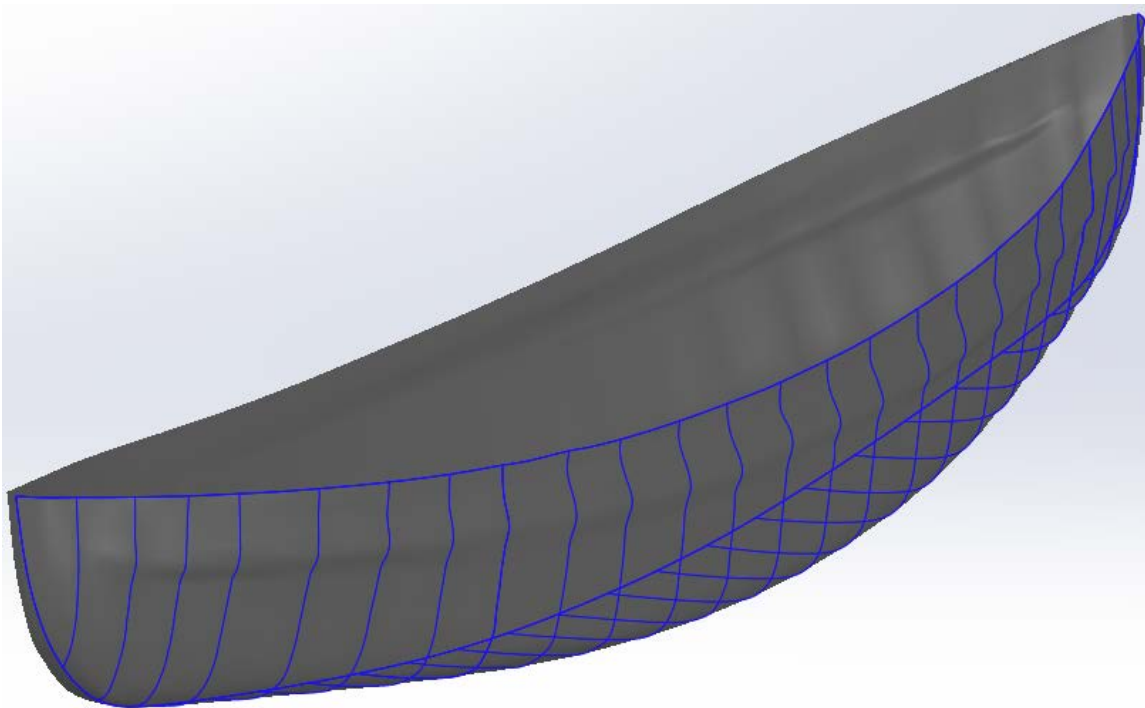


Figure 11 Completed CAD model.

In comparison with the other two methods discussed earlier in this paper, the *FARO Laser Scanner* took more time and effort for setup, however the trade-off was that probing the surface contours resulted in a much more manageable dataset. The results of importing the contours and incorporating them into a lofted geometry in Solidworks were ideal. The contours were mathematically smooth and provided closure on the entire surface in symmetry.

After obtaining a high-fidelity 3D model of the canoe, the next steps involved converting into the mold geometry. To accomplish this, the data set was transformed again – essentially turning it inside-out. Structural support elements were added to establish the resulting shape that would become the printed mold (Figures 12 & 13).

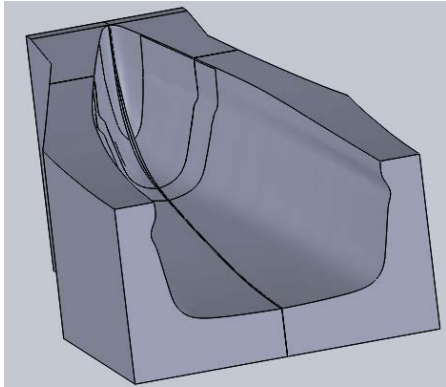


Figure 12: Half-shell showing support structure

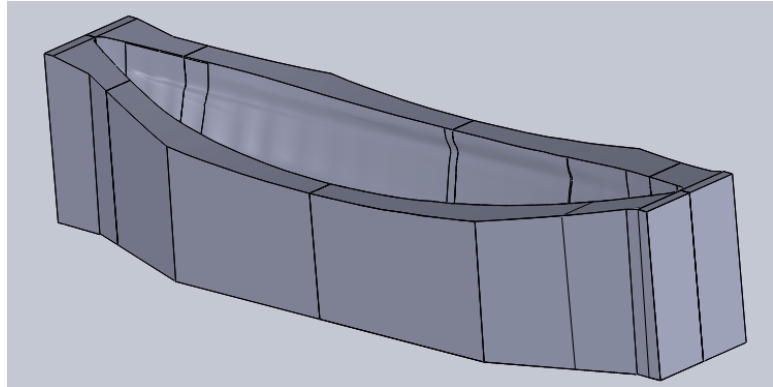


Figure 13: Full CAD mold assembly

The success of numerous printing projects incorporating the Cincinnati BAAM system has indicated building in the z direction provided the greatest detail control. Considering that the rocker and gunnel are the unique features of this version of the *Ocoee* canoe, this was the intentional build direction. With a vertical print limitation of six feet, a plan to section the canoe's overall length was prerequisite. Thus, four sections: bow port, bow starboard, stern port, and stern starboard were sectioned in the CAD data for the final 3D print form. With the CAD complete, the saved .stl file was imported into ORNL's slicing software, where the represented structure reduced to 2D planner data in approximately one-thousand four-hundred layers (Figure 14).



Figure 14: Image of BAAM print plan

The sliced data was transferred to the BAAM and the print was started. The four pillars began to take shape, and approximately 17 hours and 1350 pounds of material later, the mold forms were complete (Figures 15 and 16). After cooling for an additional six hours, the forms were removed, aligned, and a sample fit took place (Figures 16 and 17) confirming the net shape of the printed mold.



Figure 15: BAAM print underway

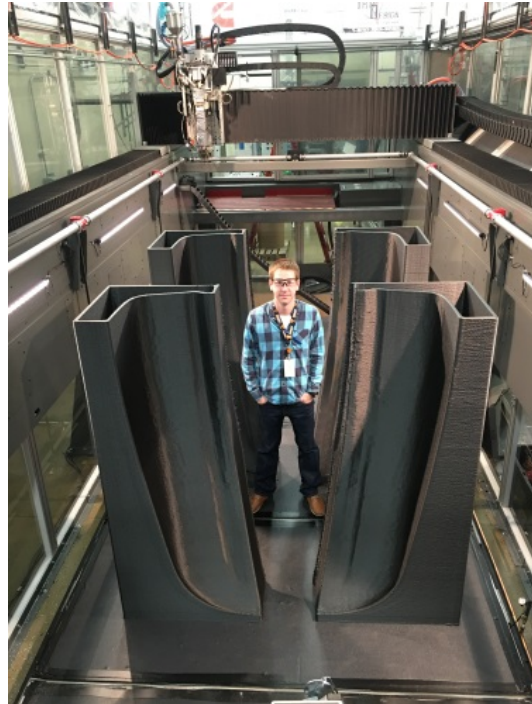


Figure 16: Print complete



Figure 17: Bow perspective of plug fit test.



Figure 18: Stern perspective of plug fit

RESULTS AND DISCUSSION

The major take-aways from this effort are many. Specifically, there was a notable usability difference between the scanning systems, and the output data files as received, were limited relative to SolidWorks CAD software. The *Sense Handheld 3D Scanner* and the *Creaform Go!SCAN 3D* differed by a factor of 100 in outright affordability, however the end result was common – an unusable data format. Table 1 compares the pros and cons of the 3

scanners used in this work. Secondly, the success of the transition from the *FARO Laser Scanner* data to a usable sliced dataset, although requiring several additional processing steps through CAD, was encouraging and has set precedence for the method for shape transference here at the MDF. Finally, the condition of the mold as compared to net-shape was extremely encouraging.

Table 1: Comparison of Scanners

Scanner	Medium	Resolution	Price Point	Pros	Cons
<i>Sense Handheld 3D Scanner</i>	White Light mono-pickup	0.9mm @ 0.5m	\$400	Lightweight, Portable with laptop	Level of detail limited by monocular pick-up; Requires detailed contour for successful data acquisition
<i>Creaform Go!SCAN50</i>	White Light Stereo-pickup	0.5mm @ 0.4m	\$40,000	Lightweight, Portable w/ laptop	Hyper data collection overwhelms the CAD system; Requires treating / marking of the entire surface contour for successful data acquisition
<i>FARO Laser Tracker X</i>	Red Laser Class 1, line of sight return	0.011mm @ 20m	\$37,000	Systematic; Controlled to the data set desired	Post processing more in-depth for the results desired

CONCLUSIONS & FUTURE WORK

The reproduction of legacy watercraft employing 3D printing requires capturing the object's contours, transforming into a usable / readable format (CAD) for the computer's slicing software (.stl), and then physically creating that object. This paper presents the results of using three different scanner systems to capture a form modeled after the *Ocoee Bluewater canoe*. As mentioned with the *Sense Handheld 3D Scanner* and the *Creaform Go!SCAN 3D* the resulting scans of the existing canoe plug produced a data set that was either incomplete or overwhelming in size. Thus, surface probing with the FARO laser scanner was enlisted to measure the contours along the length of the watercraft, and it was concluded that the use of surface probing with the *Faro Laser Tracker X* was the optimal scanning method of the three tested units. The tight fit of the scanned plug in the printed mold verified the technique's success.

Future efforts will be to take the CAD data from the original form and modify to a slightly smaller version to accommodate the targeted end user of this canoe. Next the flange areas will need to be designed in order to manufacture multiples of the canoe from the form. Traditional surface finishing of the mold ‘gelling’ will be next along with the preparation of a silicon bag for the VARTM (vacuum assisted resin transfer molding) process. Lay-up of materials, bagging, and infusing will create the part form as the next step. Finally, part retrieval, minor subtractive or material trimming will take place, and final fitting of the gunnel supports, seating installation, and surface finishing will take place to produce the new version of the legacy part that will be ready for water testing.

This work was conducted under CRADA NFE-15-05575 as a Technical Collaboration project within the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF) sponsored by the US Department of Energy Advanced Manufacturing Office (CPS Agreement Number 24761). Research sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

References:

- [1] Curran, S., Chambon, P., Lind, R., Love, L. et al., "Big Area Additive Manufacturing and Hardware-in-the-Loop for Rapid Vehicle Powertrain Prototyping: A Case Study on the Development of a 3-D-Printed Shelby Cobra," SAE Technical Paper 2016-01-0328, 2016, doi:10.4271/2016-01-0328.
- [2] "History - Magnum Venus Products," *Magnum Venus Products History Comments*. [Online]. Available at: <http://www.mvpin.com/us/history/>. [Accessed: 03-May-2016].
- [3] "Sense™3D scanner," *Sense 3D Scanner*. [Online]. Available at: <http://www.3dsystems.com/shop/sense/techspecs>. [Accessed: 03-May-2016].
- [4] "Technical Specifications: Go!SCAN 3D," *3D Laser Scanner, Coordinate Measuring Machine and 3D Scanning*. [Online]. Available at: <http://www.creaform3d.com/en/technical-specifications-goscan-3d>. [Accessed: 03-May-2016].
- [5] "04REF201-134-EN - FARO Laser Tracker X Tech Sheet.pdf". [Online]. Available at: http://www.trosol.com/laser_tracker/downloads/04REF201-134-EN%20-%20FARO%20Laser%20Tracker%20X%20Tech%20Sheet.pdf. [Accessed: 03-May-2016].