Visualization of Height Field Data with Physical Models and Texture Photomapping

Dru Clark
Michael Bailey[1]

University of California at San Diego and San Diego Supercomputer Center

ABSTRACT

This paper discusses a unique way to visualize height field data – the use of solid fabricated parts with a photomapped texture to display scalar information. In this process, the data in a height field are turned into a 3D solid representation through solid freeform fabrication techniques, in our case Laminated Object Manufacturing. Next, that object is used as a 3D "photographic plate" to allow a texture image representing scalar data to be permanently mapped onto it. This paper discusses this process and how it can be used in different visualization situations.

Keywords: Computer graphics, object modeling, scientific visualization.

INTRODUCTION

Effective visualization of height, or elevation grid, data is a recurring theme in scientific visualization. A *height field* problem is characterized by a grid of points in X and Y each with an associated Z height. The collection of heights is turned explicitly (mathematically) or implicitly (by human eye-brain fusion) into a 3D surface. By turning the grid of heights into a surface, the viewer can better look at the dataset as a whole, discerning trends and patterns and discovering anomalies.

The most common use for height fields is to visualize terrain surfaces ([KELLER93], [WOLFF93]). In this case, X and Y are longitude and latitude, and the height is elevation above or below a base reference. It is from this application that the synonym for height field, *elevation grid*, is derived. Height fields are also useful for visualizing scalar values mapped to a data surface. Examples of this sort of application include stresses in plates, strain energy density, temperature, pressure, and ozone density ([KAUFMANN93], [KELLER93], [WOLFF93]).

A graphical display of a height field data suffers from all the same problems as the display of any other 3D surface. The image itself is displayed on a flat piece of glass. It is not really 3D – it only can be made to appear 3D. Therefore, we must play a variety of graphics "tricks" to fool the user into thinking the surface is real enough to be used as a way to acquire insight into the data. We typically turn to perspective, hidden surface removal, light source shading, texture mapping, binocular display, and dynamic rotation to give the user the proper sense of 3D-ness.

But, in the end, all of these techniques still have major shortcomings:

- It is still a flat piece of glass or paper. Even binocular displays do not force the human eye to change focus when moving from the front of the scene to the back.
- It only uses one sense, the sense of sight. As experiments show (e.g., [SCALETTI91]), there is much to be gained by reinforcing one sense's intake of information by simultaneously presenting it to another.
- Many of these tricks are difficult to take somewhere else and show other people. Flat hardcopy cannot capture all of the 3D cues. Once we leave the workstation environment, some of the best cues, such as dynamic rotation and binocular vision, go away.

The need to have better ways of looking at height field data, particularly away from the workstation, led us to investigate the use of 3D solid model-making as a mainstream form of scientific visualization display.

---

[1] UCSD / SDSC
PO Box 85608
San Diego, CA 92186
dru@sdsc.edu, mjb@sdsc.edu

SOLID FREEFORM FABRICATION

This project was done under the auspices of a research and development project at the University of California at San Diego and the San Diego Supercomputer Center called the TeleManufacturing Facility (TMF). The TMF has created an automated capability on the Internet to manufacture 3D parts. It is undertaking the necessary research and development to make it viable for engineers and scientists to use over long distances. To do this, we are using a technology known as *rapid prototyping* (RP), or *solid freeform fabrication* (SFF).

There are many forms of solid freeform fabrication ([BAILEY96], [BURNS93], [JOHNSON94]). The most well-known is stereolithography, commercialized by 3D Systems, Inc., which manufactures prototype parts from a liquid plastic resin. Other SFF technologies add layers of various materials, extrude plastic, or solidify powder. But, no matter what process is used, SFF is characterized by being an *additive manufacturing process* instead of a subtractive process as is found in traditional methods such as numerical control machining or electrical discharge machining.

Additive manufacturing process have some definite advantages when fabricating 3D parts for scientific visualization:

- The parts can have almost arbitrary geometric complexity.
- The fabrication can be setup with little or no human preparation.
- The fabrication can proceed with little or no human intervention.

The first item above is especially advantageous for scientific visualization. One of the problems with subtractive manufacturing methods is that whatever is doing the subtracting needs to get in somewhere to remove material. For some parts, the complexity of the geometry prohibits getting the cutting tool in as far as it needs to go, or at least makes it difficult. A good example would be a fairly complex molecule such as a protein ([BAILEY95], [BAILEY96]). The deep channels and grooves would make it almost impossible to get a machine tool in there without accidentally gouging some portion of the part that we mean to keep.

The second and third items above are also significant for scientific visualization. Again using a complex molecule as an example, many parts that come up in scientific visualization have both a top and a bottom that require fabrication. (Height fields are generally not that way, but other visualization applications are.) In typical subtractive methods, such parts would need to be machined on the top and then flipped over to machine the rest. To flip it over correctly, a set of fixtures and clamps would need to be designed and a process would have to be put in place to re-register the part once it has been flipped and clamped. This ensures that the part is indeed where the machine tool thinks it is. If this is not done, then the features on the top half will not align with the features on the bottom half.

The point is that fabrication methods for visualization must not require much manufacturing knowledge, or they will not be used. We like to call this *amateur fabrication*, which is what you are really doing when a non-engineer tries to make a physical prototype of something. As has been accomplished with paper and film hardcopy (e.g., [NADEAU91]), successfully integrating solid hardcopy into scientific visualization must not require detailed understanding of the process.

THE TELEMANUFACTURING FACILITY PROJECT

To this end, the TMF project is using the World Wide Web as an interface to the SFF process. As shown below in Figure 1, users can submit their geometry STL files from their favorite browser, have those files automatically checked for geometric and topological consistency, have a corrected STL file returned, or have the file queued for fabrication. When the part is being fabricated, the web page can also be used to get feedback on the manufacturing process, including seeing video images from cameras surrounding the machine.

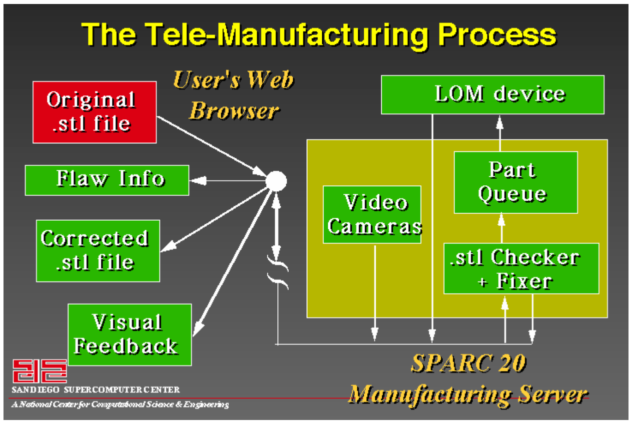

Figure 1: TeleManufacturing on the WWW

In the TMF, we are using a *Laminated Object Manufacturing* (LOM) device, from Helisys, Inc. [LOM95]. In the LOM process, a 3D part is built from layers of paper each .004” thick, or from layers of plastic each .005” thick. A layer of glue on the paper is heated by a roller to laminate it to the layer underneath it. A CO_2 laser is then used to cut the outline of the cross-section of the part at this level. The laser then crosshatches everything on this layer that is not part, so that it can later be plucked away as cubes of scrap. This results in a part that looks, feels, and acts like wood.

Figure 2 below shows a schematic of the LOM process. Figure 3 shows the TMF’s LOM 1015 machine with its doors open.

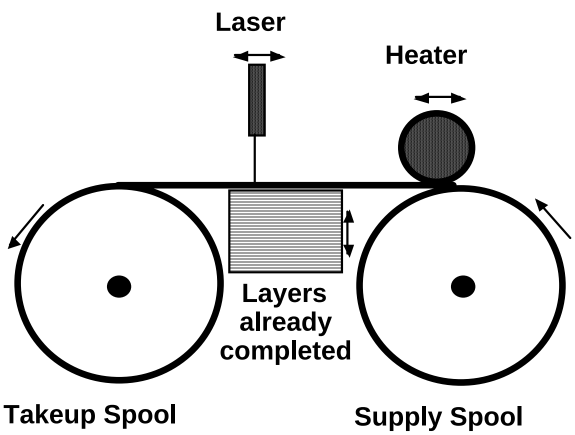

Figure 2: The Laminated Object Manufacturing Process

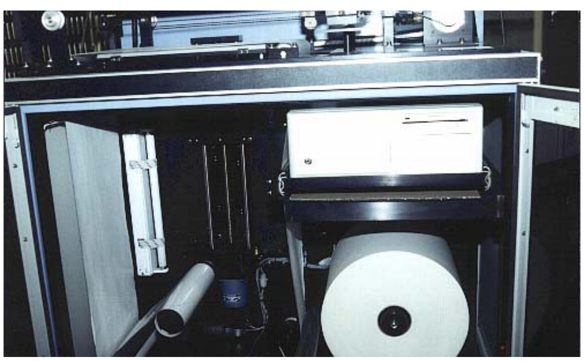

Figure 3: The Helisys LOM 1015 Machine at the TMF

CONSTRUCTING THE 3D MODEL

To test the idea of using the LOM machine to display a height field, we selected an infrared satellite photo of hurricane Luis [PURDUE95]. The image measured infrared energy, not visible light. While visible light satellite images make better posters, images sampled in various infrared bands contain more specific information about the situation. The nature of infrared photography allowed for a height field to be constructed directly from the image. Higher infrared intensities are indicative of hotter regions in the dataset. The pixels represent the various temperatures in the atmosphere at that time. The temperatures are related to the elevation of the bodies. Thus, the pixel intensities could be scaled and mapped to a gridded height field. The cold cloud tops became peaks and the warmer land and sea became troughs.

Figure 4 shows the original satellite photo of the hurricane with the intensities inverted so that the higher intensities represent colder temperatures, which in turn represent higher elevations.

Figure 4: Intensity-Inverted Hurricane Luis Infrared Satellite Photograph

The original image had been processed to include important surface data such as longitude and latitude lines and country borders that would allow us to register the size and location of the clouds with ground truth. These pieces of information showed up in the photograph as light-colored pixels, and thus became part of the height field data.

This grid of heights was then triangulated and converted into the STL file format. The STL, or stereolithography, file format is the solid freeform fabrication industry *de facto* standard for representing 3D parts. In it, one lists the 3D triangles that bound the outer skin of the part. Because 3D part representations must be legal solids, we also needed to triangulate the four sides and the base. For more details on this process, see [BAILEY96]. Figure 5 below shows the triangulated STL file of the hurricane height field as seen with the TMF’s STL-preview program:

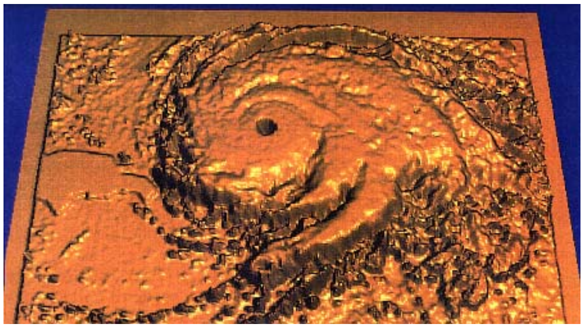

Figure 5: Triangulation of the Hurricane Cloud Model

The solid model was built on the LOM machine. The dimensions were 8”x6”x1”. The part required 250 layers of paper, and took about six hours to build. The result was a solid relief map of the hurricane image, shown below in Figure 6.

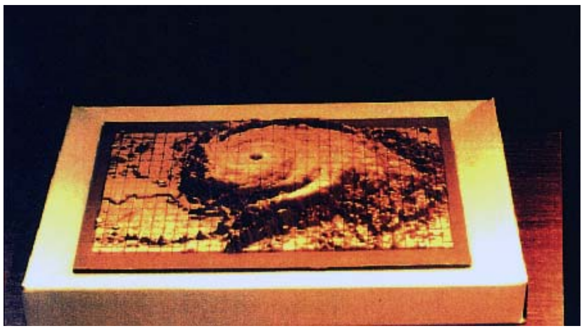

Figure 6: Hurricane LOM Model

Close inspection of Figure 6 shows one of the attributes of the LOM process that makes it especially nice for terrain-type surfaces. Because the paper is white and the laser scorch is brown, the model is automatically covered with contour lines. In this application, we were about to cover those contour lines with the photo texture map, but in other height field applications, the automatic contour line by-product has been an excellent visualization enhancement.

PREPARING FOR THE PHOTOMAPPING PROCESS

We decided to consider photomapping as a way to apply that extra detail. Photomapping is the process of superimposing data on top of a 2D photographic image to increase the visible information. The method is common on aerial and satellite photographs. By superimposing grid lines, borders, and names, the photograph is enhanced. We could not photomap directly on the LOM model, though. Because this use of the LOM process involved paper, the models could not get wet. Instead, the solid model was used to construct a silicone mold. The molded casts proved to be valuable for another reason: it allowed for multiple test models to be built quickly and inexpensively. The final test models were made with an opaque two-part polyurethane casting compound which gave them a plastic look and feel. Future models will take advantage of new LOM materials such as plastics and composites which maintain their structure in moisture.

PHOTOMAPPING IN THREE DIMENSIONS

Traditional photomapping techniques combine two dimensional data and two dimensional photographs. The method described here involves superimposing two dimensional data on top of a three dimensional solid model. By applying traditional photographic techniques to the solid models a new visualization tool is created.

Liquid Light from Rockland Colloid Corporation [ROCKLAND] was selected for the photo-sensitive emulsion. This is a silver-halide sensitizer that can be applied to most solid surfaces. Rockland suggests a surface preparation so the emulsion bonds to the model. A clear polyurethane and an oil based primer were tested with the latter giving the best results. This base coat was applied and set to dry. The model was then coated several times with the photo-sensitive emulsion. Each coat was applied with a soft brush and set to dry. The emulsion must be applied in a darkroom and the models stored in light safe containers while drying. Three individual layers were applied to maintain a desired contrast and an even coat. Ideally, spraying this coat on the model would even out the finish as well as speed up the process.

Once dried, the models were ready to be exposed to the satellite image. A negative of the infrared image was produced on 35 mm film. The image for the negative differed from the one used for the solid model only by the added information. A standard photo-enlarger was used for the image projection. The registration information was used to visually align the image to the physical model. Guiding tracks were attached to the enlarger base to insure that each model was in alignment.

One difference between projecting onto a 3D model instead of 2D enlargement paper is the focal point. A sharp image on the entire surface proved nearly impossible. Because the model was not planar, the focal depth of field had to be much greater or the model displacement had to be limited. We planned for this in the original construction of the model. The scaled values for the solid model were limited to just under an inch in order to maintain a narrow focus zone. From experience we found that most terrain maps could be kept within this range and still be effective. This, of course, depends on the individual data and desired results. The region with the most detail was the base which contained text and border information. This had to be in sharp focus. It was determined that the focal point should be set about one third of the way above the base. This maintained the sharpest focus around the text and distributed the rest. Greater depth of field can be achieved with other enlarging techniques. We set the aperture to the smallest opening to achieve the greatest focal zone. The exposure time was increased to balance out with the reduced aperture setting. For the Liquid Light at these setting one minute did the trick but this will vary by equipment. Several test plates were exposed to determine the best parameters.

Rockland suggests that a small amount of developer be mixed into the emulsion. This caused the image to start developing just after exposure. The developing process is the same for 2D prints except that a much deeper container is needed to hold the chemicals. The model was submerged in the developer bath consisting of one part Kodak Dektol to two parts water. The model was rinsed with water as a stop bath, not the normal acid bath used with paper. The model was fixed with hardening fixer, also from Kodak. The last step was a simple wash with water for ten minutes and letting the part dry. The dried emulsion has a high sheen which can be covered with a matte or semi-gloss finish coat. When viewed from the front the photomapped model looks like the printed 2D hardcopy. When the model is rotated the hurricane jumps above the base and the immense size in all directions becomes apparent. Figure 7 shows the final product.

Figure 7: Finished Hurricane Display

CONCLUSIONS AND FUTURE WORK

This method worked quite well for the application. It is an effective way to create a 3D, texture-mapped, hold-it-in-your-hand, data-accurate hardcopy of a height field. As height fields find use in a variety of visualization applications, this method could be applied to other satellite images, DEM data, bathymetry, or mathematical surfaces.

This process is fairly labor intensive but as suggested earlier the use of plastic and composite materials to built the original solid model is a major improvement. This would allow for quick single runs or act as a positive for the mold in large runs. The X and Y dimensions used for this model can be expanded. Rockwell suggests that exposure can be by enlarger or projector. The limiting factor here is how large of a developer bath can be handled. It has been proven that size constraints of the LOM machine can be expanded by tiling plates together.

We feel that this will be an even better technique when we are able to do it in color, which we are currently pursuing. One variation on this idea has been to use the LOM model as a screen and project dynamic information with a video projector. This display technique allow for ever changing data such as weather, population, even plant life to be projected on to DEM data based solid models. At that point, we hope to use it as a general model coloring tool, even in non-height field applications. An application in which we are particularly interested is using color in this way to display electrical charge around the surface of a complex molecule model, although clearly the projections will be trickier.

WEB PAGE

For more information see:

`http://www.sdsc.edu/tmf`

ACKNOWLEDGEMENTS

This work was supported by the National Science Foundation under grant MIP-9420099.

The authors acknowledge Sun Microsystems for their generous donation of the SPARCstation 20 used as the manufacturing server.

REFERENCES

[BAILEY95]
Michael Bailey, "Tele-Manufacturing: Rapid Prototyping on the Internet with Automatic Consistency-Checking," *IEEE Computer Graphics and Applications*, November 1995.

[BAILEY96]
Michael Bailey, "The Use of Solid Rapid Prototyping in Computer Graphics and Scientific Visualization, " SIGGRAPH Course Notes for *The Use of Touch as an I/O Device for Graphics and Visualization*, 1996.

[BURNS93]
Marshall Burns, *Automated Fabrication*, Prentice-Hall, 1993.

[JOHNSON94]
Jerome L. Johnson, *A Unified Description of All Free Form Fabrication Technologies Based on Fundamental Principles,* Palatino Press, 1994.

[KAUFMANN93]
William J. Kaufmann and Larry L. Smarr, *Supercomputing and the Transformation of Science*, Scientific American Library, 1993.

[KELLER93]
Peter Keller and Mary Keller, *Visual Cues: Practical Data Visualization*, IEEE Press, 1993.

[LOM95]
Laminated Object Manufacturing product literature, Helisys, Inc., 1995.

[MILLER94]
John F. Miller, "CAD Requirements for Rapid Prototyping Tutorial," *Rapid Prototyping & Manufacturing '94,* Society of Manufacturing Engineers, 1994.

[NADEAU91]
David Nadeau, T. Todd Elvins, and Michael Bailey, "Image Handling in a Multi-Vendor Environment," Proceedings of *IEEE Visualization '91*, October 1991, pp276-283.

[PURDUE95]
`http://wxp.atms.purdue.edu/hurricaner.html` – Department of Earth and Atmospheric Sciences, Purdue University.

[ROCKLAND]
Liquid Light Photographic Emulsion made by Rockland Colloid Corp. of Piermont N.Y.

[SCALETTI91]
Carla Scaletti and Alan Craig, *Using Sound to Extract Meaning from Complex Data*, NCSA videotape, February 19, 1991.

[SERWAY96]
Raymond Serway, *Physics for Scientists and Engineers*, 4th edition, Saunders College Publications, 1996.

[STL89]
"Stereolithography Interface Specification," 3D Systems, Inc., October 1989.

[WOLFF93]
Robert Wolff and Larry Yaeger, *Visualization of Natural Phenomena*, Springer-Verlag, 1993.

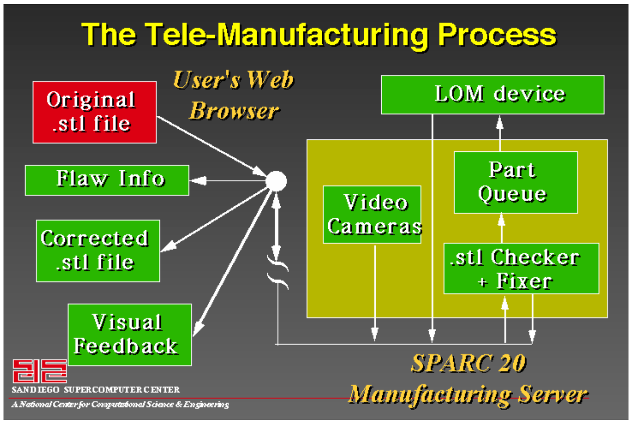

Figure 1: TeleManufacturing on the WWW

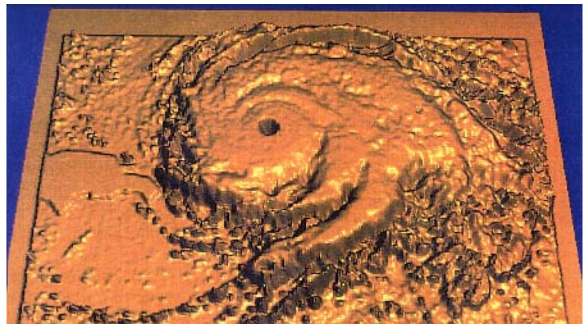

Figure 5: Triangulation of the Hurricane Cloud Model

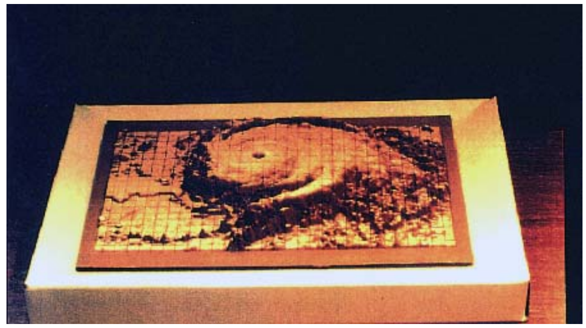

Figure 6: Hurricane LOM Model

Figure 7: Finished Hurricane Display