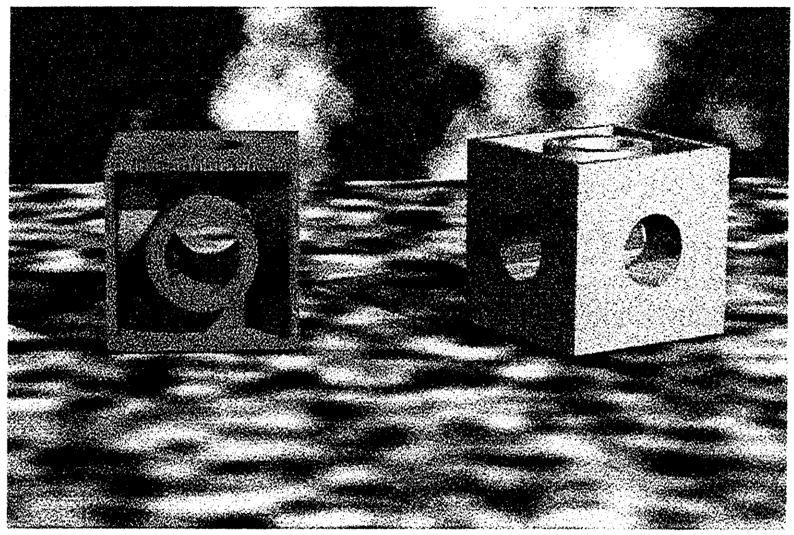
Reverse Engineering: Practical Considerations for Rapid Prototyping

Alair Griffin[1], Scott McMillin[1], Curtis Griffin[1], Dr. Charles Knox[2]
[1]Lone Peak Engineering, Inc.
[2]Image3, LLC

Abstract

It is now possible to generate three-dimensional (3D) solid models of extremely complicated systems from which full plastic replicas can be generated using a variety of rapid prototyping technologies. The cycle time has been reduced to several hours, where it previously took months to produce a comparable prototype. The process of taking a design into the 3D environment, whether UNIX- or PC-based, is getting easier and fairly straightforward.

The design engineer interested in producing a 3D model from unique data sets such as computer tomography (CT) or magnetic resonance (MR) image data is particularly concerned with time, cost, accuracy, and conversion problems. This paper presents an approach that Lone Peak Engineering, Inc. (LPE) has used that allows them to successfully handle CT and MR data for reverse engineering (RE).



3D Models Presented in a 3D Environment

Introduction

Flexibility and "time-to-market" are key factors for any company to remain competitive in either the defense or commercial marketplace. The ability to rapidly prototype products has to be an integral part of any agile manufacturing scenario in order for a company to remain competitive. Rapid prototyping refers to the practical ability to build high-quality physical prototypes as an engineering aid. With rapid prototyping, full-scale models can be built in a variety of materials using a large number of commercial systems. With the advent of rapid tooling techniques, RP has started to transition into a rapid manufacturing technology. Responding to pressure for shorter time-to-market cycles, industry has been pushing for functional parts fabricated with engineering materials, not prototypes made of non-structural materials. Driven by the high cost and long lead time required to make tooling, and threatened by the growing shortage of skilled tool and die makers, rapid prototyping may offer ways of producing tooling quicker and more affordably.

Most reverse engineering approaches involve imaging or digitizing an object and then creating a computerized reconstruction that can be integrated, in 3D, into the particular design environment. Relying on volume visualization technology, a fundamental technique for interpreting and interacting with large, 3D data sets, Lone Peak investigated the potential of reverse engineering as an integrated step in rapid production and agile manufacturing. Over the past four years, LPE has evaluated the potential of integrating CT-based reverse engineering with the following rapid prototyping systems (RP): Laminated Object Manufacturing (LOM)™, Fused Deposition Modeling (FDM)™, Stereolithography (SLA)™ and Selective Laser Sintering (SLS)™. During this time, they demonstrated that it is possible to reconstruct objects from CT data and to produce prototypes using virtually any commercial RP system. This paper presents a summary of practical considerations for the designer or engineer considering implementing such CT-based reverse engineering into their operations.

First Step: Reconstruction Software

Literally thousands of image reconstruction software packages are available. Most target the medical market and few support the file formats recognized by rapid prototyping systems or other equipment, such as numerically controlled machines. Without software specifically designed to address conversion of volumetric data to complex design and rendering, the majority of image reconstruction packages are not be able to deliver what is needed for a true reverse engineering application. Lone Peak currently uses a state-of-the art imaging software package, (*Velocity2™)*[1] to create computer reconstructions of 3D objects taken directly from volumetric data sets. This package directly supports a rapid prototyping interface. The software package consists of several programs:

Image. An image processor and high resolution surface reconstructor, featuring several classes of functions, including radiometric, filtering, morphological and geometric operations. Sequences of image processing operations can be recorded, saved to script files and used later to process the same or different image sets. Up to eight region-of-interest masks can be defined for each image and subsequently used to define objects to be reconstructed. **Image** can read data in a number of different image formats, including formats used on the more common CT and MR scanners.

Surfer. A high resolution surface generator that processes the volumetric image data sets and stores a geometry file containing a winged-edge, linked list of surface polygons that describes the 3D model. **Surfer** can extract surfaces using gray value isosurface definitions, region-of-interest masks as defined in **Image** or combinations of both.

Display. A visualization program that displays and animates the 3D models using sophisticated graphics techniques, including: interactive viewpoint control, multiple light sources, user-defined surface material properties (ambient, diffuse, specular, transparency, emissivity), surface smoothing, and stereoscopic viewing.

PolyMerge. Reduces polygon count and file size of a 3D model by merging small surface polygons into larger ones in regions of relatively flat surface as determined using local surface curvature criteria. Local surface smoothing can also be applied prior to polygon merging, resulting in significant improvements in count reduction.

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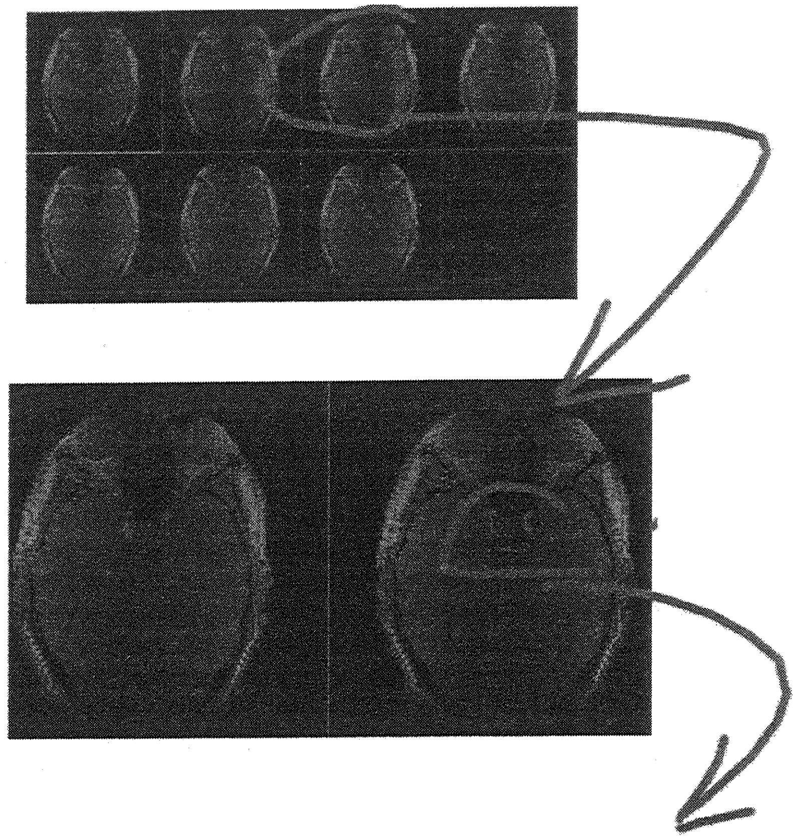
Velocity/STL. Creates STL files from the 3D model geometry data. Fault-free surfaces with all the benefits of surface smoothing and polygon merge as performed by **Display** and **PolyMerge**.

Scanning and Reconstruction

Reconstruction is the "rebuilding" of something that has been taken apart. In medical imaging the process involves rebuilding an internal view of the body from a series of images, or "slices", taken along parallel planes through the body. Each pixel in a slice represents an intensity value, the absorption of X-rays in CT imaging or the strength of the magnetic signal induced in the oscillations of hydrogen atoms in MR imaging. Once an object has been reconstructed, 3D computer visualization techniques are used to view the data.

Object slice data can be obtained in a variety of ways. Three methods: serial-section reconstruction, computed tomography and magnetic resonance imaging, are discussed in more detail below.

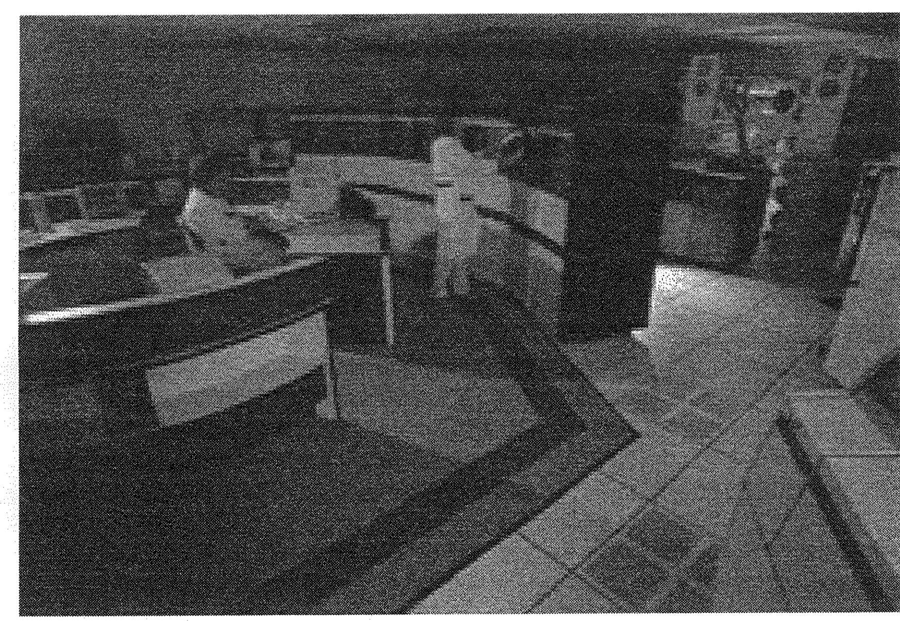


Surgery @ 2:30pm

Room 1423

Although Lone Peak has worked with a variety of scan data, due to the availability of medical and industrial scanners, they consider CT scanning as the best option for reverse engineering applications

<ins>Serial-Sectioning</ins> - In traditional serial-section light microscopy, the tissue being studied is sliced on a microtome into a number of thin sections which are then prepared on glass slides and viewed in a microscope. Then digitized images are captured of each section. To recreate the sectioned object, all of the images must be put back together again in the right sequence and with the correct geometric alignment. The technique has the advantage of being able to create extremely thin sections, but the drawbacks are the large expenditure of time, destruction of the specimen, and serious problems with tissue distortion and realignment of sections for 3D reconstruction.



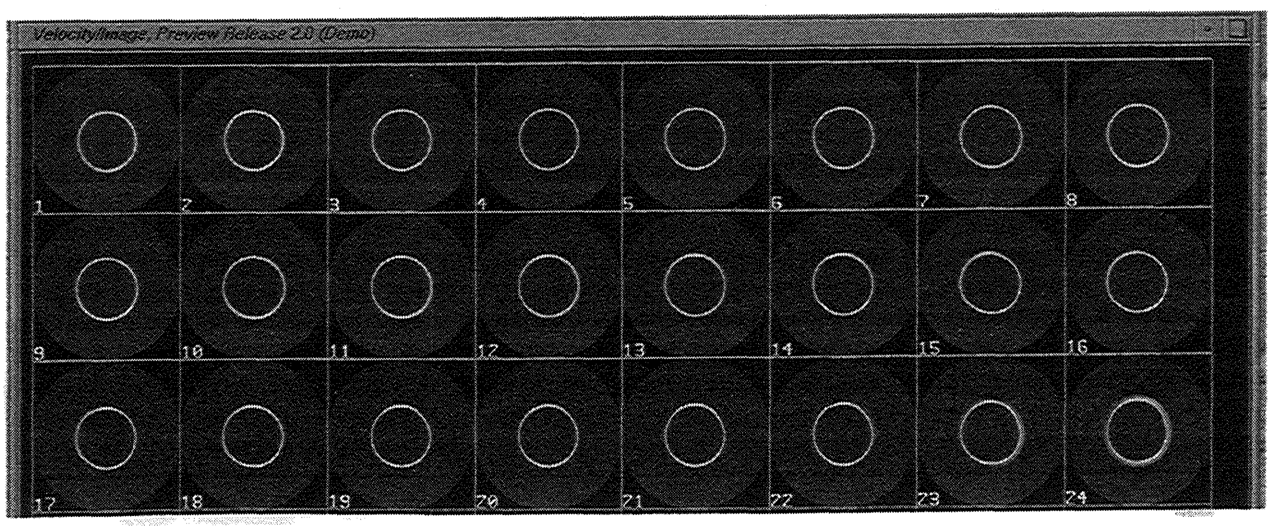
Problems with section distortion and realignment for 3D reconstruction can be reduced, if not eliminated, by forming digitized images of the cut surface of an object as thin layers are successively removed. This method has been used to create an anatomical atlas of serial-sections of the human body (Visible Human Project), and is also the basis of some industrial machines for reverse enginering (CGI). However, the methods are still time-consuming and destroy the specimen, making them of limited application for reverse engineering.

Computed Tomography - In CT imaging, a 3D image of an X-ray absorbing object is reconstructed from a series of 2D cross-sectional images. An X-ray beam penetrates the object, and transmitted beam intensity is measured by an array of detectors. Each such "projection" is obtained at a slightly different angle as the scanner rotates about the object. The 2D image is computed from the projected images using the approximate method of "back projection" or the more accurate method of inverse Fourier transformation. CT was introduced in the early 1970's as a neurological examination technique and later extended to industrial applications. It is a radiographic examination technique used whenever the primary goal is to locate and size planar and volumetric detail in three dimensions.

Current industrial CT systems can provide dimensional measurements at an accuracy competitive with coordinate measuring machines (CMMs). Of the existing methods for generating a CAD model of a physical part, only CT can nondestructively dimension internal, as well as external, surfaces. CT does not require elaborate fixturing, positioning or part-specific programming and CT has the unique ability to detect and quantify defects—a key consideration if the performance of as-built parts must be predicted via engineering models. Additionally, CT is indifferent to surface finish, composition and material; and it can measure part coordinates as fast as laser scanners—and orders of magnitude faster than CMMs [1].

Because of the relatively good penetrability of X rays, as well as the sensitivity of absorption cross sections to density and atomic number of matter, CT permits the nondestructive evaluation (NDE) and, to a limited extent, chemical characterization of the internal structure of materials [1]. Also, since the method is X-ray based, it applies equally well to metallic and non-metallic specimens, solid and fibrous materials, smooth and irregularly surfaced objects.

Magnetic Resonance Imaging - In MR imaging, the device acquires a number of cross-sectional planes of data through the tissue being studied. MR imaging technology is most commonly associated with mapping of the human anatomy and is based on the oscillation of hydrogen nuclei contained in soft body parts, such as in muscles, blood and brain tissue. However, industrial uses of MR imaging exist. These include studies of mobility and diffusion of water in hydrogels used for contact lens manufacture and imaging of the flow of feedstock in membrane filtration modules [2]. In some cases, a part can be submersed in water, and the inverse of the object can be created. Reverse engineering can be accomplished by simply reconstructing the inverse of the images.



MR imaging also requires reconstruction and visualization., since all of these planes must be stacked back together to obtain a complete picture of what the original object was like.

Information Required and General Parameters Recommended

It is relatively easy to create RE digital models of a part using CT. First, the object of interest is fastened to the platen of a suitable CT system and is scanned. Generally, standard machine tool hardware is available for clamping the part to the platen. Occasionally, a special fixture may be necessary to keep it from shifting during a scan. No special pre-programming or positioning is required, and scanning can begin as soon as the part has been secured to the platen. The scan data may consist of a few slices, a stack of planes, or a full volumetric image.

The following list presents information and/or parameters that you will have to determine before you scan an object.

1. Type of scanner: You will need to determine the model and make of the CT scan machine. Then check to make sure that your image reconstruction software can translate the data.

2. Kind of scan: Axial or helical

3. Slice Thickness: 1.0 mm recommended

4. Scan spacing: 0.5 mm or at least one-half the smallest dimension of interest

5. X-ray strength

6. Resolution: Options include image dimensions of 256 x 256, 512 x 512, and 1024 x 1024 pixel and 8, 16 or (on some machines) 32 bits/pixel.

7. Field of View (FOV): Object imaged should fill the field of view without extending beyond it.

8. Position: Long axis of the object should be parallel to the bore of the scanner. Generally, scans should start just off the object and finish off the other side of the object (so that the entire object is imaged). Objects to be scanned should not be taped down or placed on similarly dense objects, that will show up in the scan.

9. Artifacts: If significant variations in material densities exist within the object to be scanned, distortion can be experienced. In the case of metal artifacts, the distortion can be severe. The scan protocol can and should be adjusted to take into account the presence of artifacts.

10. Slice Time: 2 second/slice is recommended

Images reconstructed at 512 x 512 pixels with a 16 bits/pixel resolution should require about 0.5 Mbytes of memory per slice. Average data sets can be expected to range from 25 to 100 Mbytes [3]. From the image data, the reconstruction software is then used to extract part contours and/or surfaces, as the case may be. Many thousands of internal and external measurements are quickly generated from the data. Depending on the amount of data and performance of the software, processing takes from seconds to minutes on a UNIX-based workstation. Since penetrating radiation is used, there is no inherent difference between inside and outside, hidden or visible. All features in the object are present in the image data and can therefore be extracted by the software with no penalty in scan time. Moreover, defects are captured as well. If they are important, they can also be extracted and characterized. If only an ideal description of the part is important, defect information can be discarded. The end result is a 3D model that should be exportable, in different file formats, to allow interfacing with other design environments.

Medical and Industrial CT Scanning

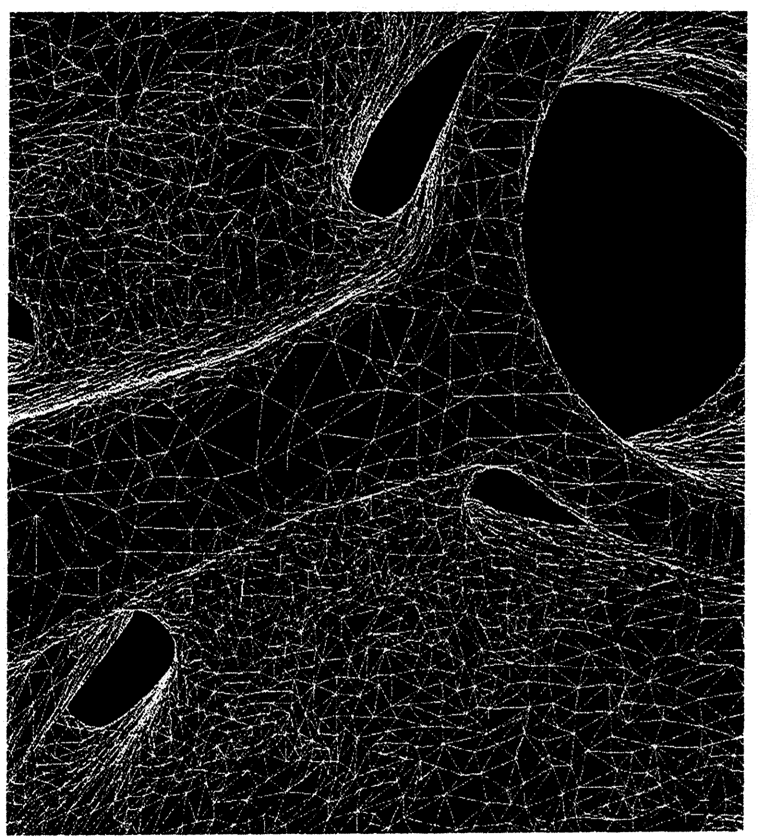
Lone Peak has found that scan time on hospital scanners is lower cost than the industrial scanners and much lower cost than laser scan systems. However, there are issues that should be considered before using hospital-based CT systems.

A major consideration, when using hospital scanners, is that your part might get bumped due to patient load requirements. Medical technicians may also insist that you provide specific scanning protocols written for your RE components. Medical scanners may not be able to get the resolution that you want. With hospital CT scanning systems you can typically expect the largest matrix to be 512 x 512 pixels versus 1024 x 1024 for an industrial CT system. The lowest FOV would be 9.6 cm which would result in an X-Y pixel dimension of 0.19 mm x 0.19 mm (where Z resolution is 0.5mm) [4].

Industrial scan costs may be higher than a local hospital and they may not be located close by. The industrial CT systems are well suited for large parts or thick-walled metal parts that would require high-intensity scanning. Aracor, an industrial CT system manufacturer, reports maximum part weight of 1000 lbs and maximum working volume of 20" x 20" x 24" for one of their systems [5].

Dealing with Artifacts

When there is a severe artifact present in the area of interest, such as a metal pin in a jaw bone, the X-ray strength and intensity must be maximized in order to reduce the effect of the artifact [6]. Slice thickness is important when a metal artifact is present. The slice thickness will depend on the amount of signal noise in the slice as opposed to spatial accuracy. To allow for the distortion, the slice thickness may vary from 3 mm to 4 mm depending on the spacing. Although not always practical, the simplest solution is to remove the artifact.



Accuracy Issues

With good technique and data, CT scan accuracy generally falls within $\pm$ 20% of the slice data. For a 1 mm slice this would equal $\pm$ 0.2mm [6]. Accuracy of the reconstruction can be influenced by the skill of the image reconstruction operator and the strength of the mathematical algorithms within the reconstruction software. Accuracy of the re-engineered components will also be influenced by the rapid prototyping or tooling technique used to produce the physical representations.

Slice or scan spacing is critical for 3D model reconstructions, and should not be confused with slice thickness. Anything over 3mm is not acceptable for complex structures. Slice spacing determines spatial accuracy. The accuracy in the Z-axis is determined by the spacing.

ARACOR's CTM 500 industrial scan system reports an accuracy of ±0.001 in. With a resolution of ± 0.007 inch and a tracking speed of 100-300 slice/hour [1]. The Aracor-built ICT-1500 CT system at Hill AFB, UT employs a 9- MeV linear accelerator and achieves a maximum resolution of 1 mm and a minimum scan time of 1 minute per slice[7].

Using their scanning system, Aracor has compared the measurement reliability of CT vs. UT and UT vs. Calipers. They found that the least reliable measurement method is UT, with a calculated standard deviation of 5.5 mils. The most reliable turned out to be CT, with a calculated standard deviation of 2.4 mils. The caliper results were in between, a calculated standard deviation of 4.4 mils. From an industry perspective, caliper measurements are generally regarded as the "gold standard," and that they provide the most reliable measurement method. Instead, ARACOR's results suggest that calipers are only marginally better than UT. Additionally, the absolute magnitude of the uncertainties were much higher than expected. Caliper measurements, for example, are assumed to be good to sub-mil accuracy, maybe a mil or two under shop conditions, certainly not 4.5 mils [7].

Model Surfaces

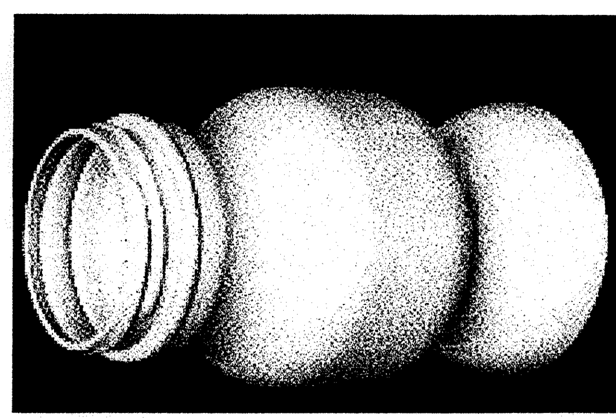
When working with scan data, LPE found that it is fairly common to produce models that have large numbers of surface polygons. Very large files can be difficult to export to rapid prototyping systems. When this occurred, *Velocity's* polygon reduction program, **PolyMerge**, was used to selectively reduce the numbers of surface polygons by collecting small triangles into larger ones in regions of the surface that are relatively flat. With **PolyMerge,** you specify this "surface flatness" as the deviation in the local surface normal vector, the "delta value", in units of angular degrees. For example, a perfectly flat surface i.e. one with a delta value of zero, will have no variation of the surface normal vectors from one triangle to the next; whereas, in regions of high surface curvature the delta value will be large. Typically, delta values of 20-30 degrees provide reductions in numbers of triangles of 30% or more in flat areas of the model without significantly affecting surface detail.

File Size Reduction

In many cases, LPE found that the original reconstruction may have surface irregularities simply due to noise, etc. in the image set. In these cases, it is advantageous to smooth the surface prior to polygon reduction to remove local surface roughness. The smoothing algorithm used in *Velocity's* **PolyMerge** (and in **Display** as well) recalculates the locations of triangle vertices as the average of a given vertex and its immediate neighbors. Significant file size reduction can be achieved, which greatly improved the ability to export reconstruction files (in the rapid prototyping STL file format) to RP systems.

CAD Interface

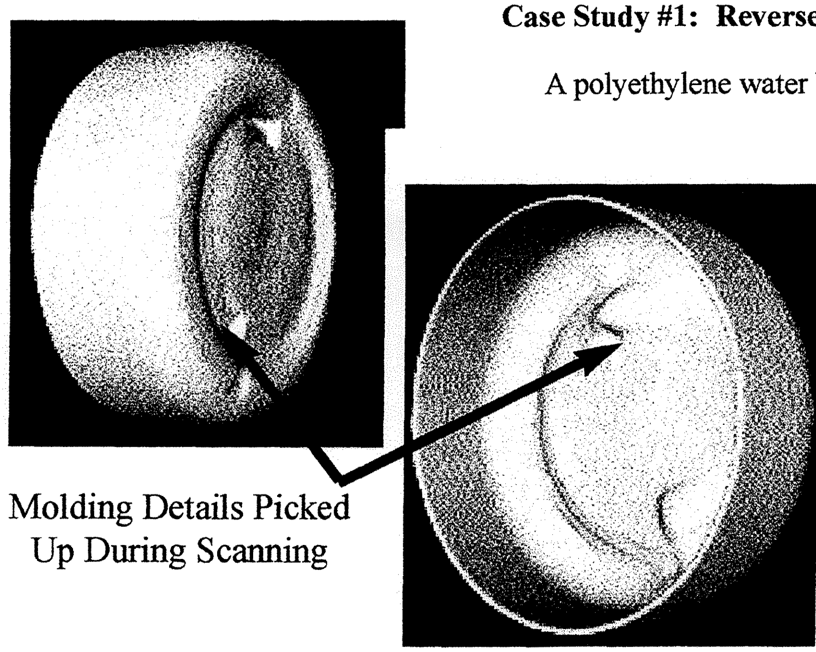
While reverse engineering from CT scans to rapid prototyping systems has been streamlined, the ability to interface universally with high-end CAD software is still problematic. Additional development is required to go beyond IGES and DXF formats so that solid models, rather than surface models can be imported into a range of CAD packages.



Case Studies

The following section summarize three case studies conducted during Lone Peak's evaluation of reverse engineering for rapid prototyping and rapid tooling.

Case Study #1: Reverse Engineering a Polyethylene Bottle

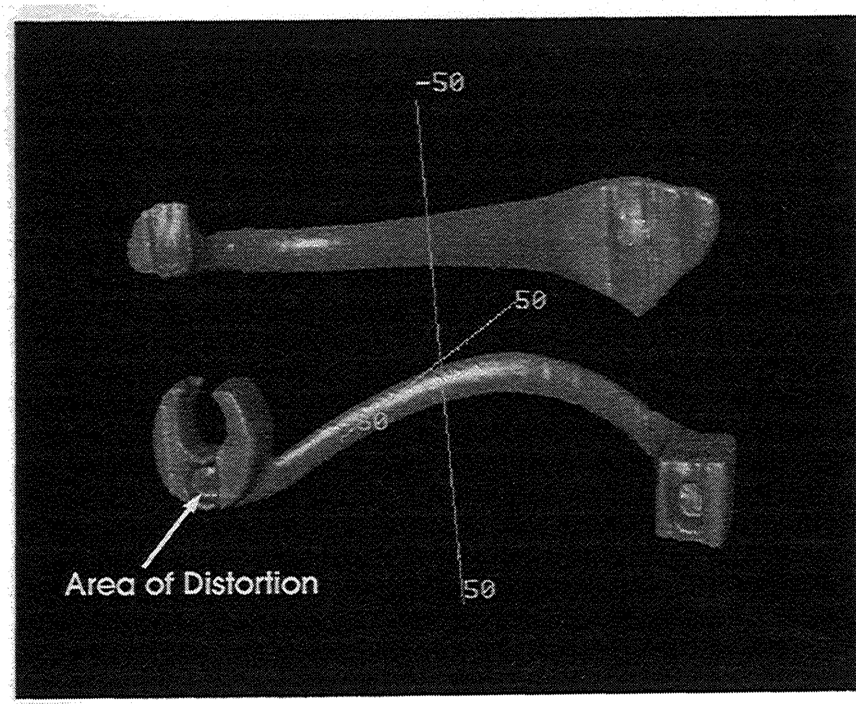


A polyethylene water bottle was chosen by Lone Peak Engineering to demonstrate reverse engineering of a thin-wall part. Lone Peak had a CT scan of the water bottle conducted. The first set of scans turned out to be unusable because, prior to scanning, a technician placed the water bottle on top of a plastic sheet. The sheet material was identical to that of the water bottle. It was not possible to easily remove the scanned image of the plastic sheet from the water bottle and it was necessary to rescan the bottle. During the second scan, another error occurred. This time the scanning technician taped down the water bottle to the foam support that had been provided by Lone Peak. Fortunately, the tape was only present in a few of the CT images and could easily be edited out.

The slice data underwent a conversion and reconstruction using the *Velocity* reconstruction software. The binary file that was produced was large; 30 Mbytes. The file was sent to a Fused Deposition Modeling system and the part was built in ABS plastic.

The reversed engineered part satisfactorily duplicated the original bottle. It was possible to screw the bottle lid from the original onto the threads of the reverse engineered prototype. The detail was sufficient that it picked up molding marks created during molding of the original bottle.

Case Study #2: Reverse Engineered Hand-Crafted Wax Handles



Hand-crafted cabinet handles were sent to Lone Peak Engineering for a reverse engineering evaluation. The handles were crafted by an artist in wax. The artist wanted to obtain a computer model of the mirror image of the handles made with a 15% enlargement. She wanted to have both the STL file and the prototypes to use as patterns for soft tooling.

Lone Peak had a CT scan of the handles conducted. The first set of scans exhibited severe distortion in certain sets of slices. This was due to metal inserts that the artist had pressed into the wax handles that allowed her to screw them onto an actual cabinet. It was necessary to remove these inserts and rescan the handles.

The CT slice data underwent conversion and reconstruction using the *Velocity* software. The STL file was produced of the mirror image the client requested. Using the file, an ABS plastic part was built using the FDM system. Overall, the scanning, reconstruction, and rapid prototyping accurately reproduced the original parts to within the limits of the FDM process, but the client felt that they still lacked some detail. She felt that she was unable to use the file. In order to achieve a more detailed prototype, Lone Peak offered to produce the prototype on an SLA system which can achieve tolerances of +/- 0.002" and/or subject the part to scanning in an industrial scanner which would have produced higher resolution scans. The client did not want an SLA prototype because she felt that the build material was artistically unacceptable. She did not wish to pursue the industrial scan options for cost reasons.

Case Study #3: Reverse Engineering a Turbine

A hand-crafted metal turbine with multiple blades was sent to Lone Peak Engineering for reverse engineering. The turbine had been used for many years as a pattern. Over time, the blades had been damaged and repaired. Since CAD data did not exist for the geometry and the pattern is still used, the client wished to have the turbine scanned, an .STL file made, and a prototype produced.

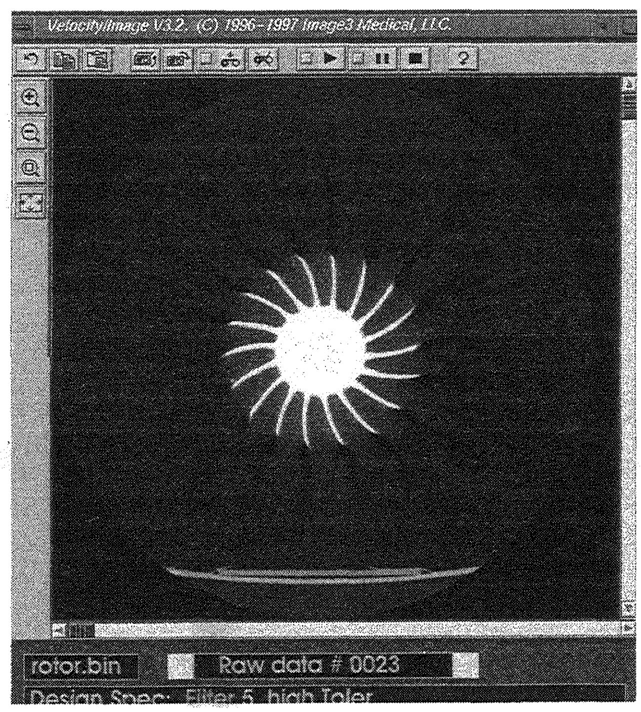
The client wanted to use the STL file in a rapid prototyping process that can rapidly produce investment castings from STL files. In this manner, they would be able to produce multiple metal parts, rapidly, and using the original turbine as the source for the castings.

Lone Peak had a CT scan of the turbine conducted. It was necessary to prototype a special support for the turbines so that it could be scanned in the proper orientation. Lone Peak has found that improper orientation of the part during scanning will result in poor data that is unsuitable for reconstruction. The scanning was conducted at a local hospital.

Once downloaded, the data underwent conversion and reconstruction. An error-free STL file was produced from the CT data. The .STL file was used to build the part using Fused Deposition Modeling out of ABS plastic. The overall tolerance achieved was +/- 0.060". The information was sent to the client. Unfortunately, the client did not understand the size of files that are generated during reverse engineering, and was unable to handle a 35 Mbytes STL file, even though LPE could handle this large file size.

Summary

Computed tomography-based reverse engineering and rapid prototyping methods are now being considered for applications in rapid tooling and manufacturing. If successful, manufacturing methods will dramatically change, which will pave the way for flexible, rapid manufacturing of a variety of components.



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