THESIS REPORT

Master's Degree

System Design for Object Reconstruction Using Information-Based Manufacturing

by Y-C. Tsou
Advisor: G. Zhang

M.S. 97-2

INSTITUTE FOR SYSTEMS RESEARCH

*Sponsored by
the National Science Foundation
Engineering Research Center Program,
the University of Maryland,
Harvard University,
and Industry*

ABSTRACT

Title of Thesis: SYSTEM DESIGN FOR OBJECT RECONSTRUCTION USING INFORMATION-BASED MANUFACTURING

Degree candidate: Yi-Chien Tsou

Degree and year: Master of Science, 1997

Thesis directed by: Dr. Guangming Zhang, Associate Professor
Institute for Systems Research and Department of Mechanical Engineering

The recent advancement of computers, both hardware and software, has led to a rapid development of information-based manufacturing. Applications of laser technology are revolutionizing the process of product development. Their numerous applications even reach the research in zoology and paleontology for object analysis and fabrication, such as fossil reconstruction. The aim of this thesis research is to implement a system design that combines advanced computer and technology developments both in hardware and in software, which utilize imaging and digitization for physical model construction.

In this thesis study, research efforts have been devoted to identifying key links related to information acquisition, manipulation, and transformation so as to prepare the data essential for constructing physical models of the objects under investigation.

Specifically, a Surveyor 3000 laser scanner located at the National Zoological Park is used for digitization of objects. Three software systems, namely, DataSculpt (developed by Laser Design), Magics RP (developed by Materialise), and Maestro (developed by 3D Systems), are employed to convert and assemble imaging data files into a single .stl file, recognizable by most CAD systems. A stereolithography apparatus, SLA-250/40, is used for rapid prototyping of physical models with high sophistication and accuracy.

Unique contributions of this thesis effort include the successful realization of a *Homunculus* facial skull constructed from only four existing fossil fragments in the world, and a reverse engineering approach to generate physical duplicates from an existing component, i.e., a distributor used in pick-up trucks.

SYSTEM DESIGN FOR OBJECT RECONSTRUCTION USING INFORMATION-BASED MANUFACTURING

by

Yi-Chien Tsou

Thesis submitted to the Faculty of the Graduate School of the
University of Maryland at College Park in partial fulfillment
of the requirements for the degree of
Master of Science
1997

Advisory Committee:

Associate Professor Guangming Zhang, Chairman/Advisor
Professor Patrick F. Cunniff
Associate Professor K. J. Ray Liu
Professor Prakash Narayan

DEDICATION

To my first baby. He passed away before I named him.

ACKNOWLEDGMENTS

I am indebted to my thesis advisor, Dr. Guangming Zhang, for his guidance and encouragement. Without Dr. Zhang's dedication and support, this research would not have been possible. I am so proud to have been able to work with Dr. Zhang. I would like to extend my gratitude to Dr. Cunniff, Dr. Liu and Dr. Narayan for serving on my thesis committee and providing suggestions for improvements in this research.

This research has been conducted under the support of the Department of Zoological Research, National Zoological Park of the Smithsonian Institution. Sincere appreciation also goes to Dr. Rosenberger for kindly supplying the Surveyor 3000 and helping the reconstruction of *Homunculus* fossils. Special thanks to Ms. Kellogg for her assistance of using DataSculpt and the Surveyor 3000.

I would like to thank the following students in the Advanced Design and Manufacturing Laboratory for their support: Xin Che, Charles Clinton, David Delalio, Lixun Qi, Mark Richardson and Rena Surana.

I gratefully acknowledge the Army of the Republic of China. The Army has provided me with full sponsorship during these past two years.

Last but not least, I thank my parents, wife and family for their love.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

Introduction

The stereolithography process has found many applications in industry because of its efficiency and accuracy. Continuous developments have made it widely applicable in manufacturing and production. Advances in hardware have increased the scope of applications for the stereolithography process. For example, in order to protect the surfaces of unique objects, laser scanning is a method which can be used to capture shape without physically touching it. Improvements have also been made in the Computer Aided Design (CAD) environment to speed up the stereolithography process.

Stereolithography is the key tool for object reconstruction. However, a system is needed to combine various hardware and software tools for conducting object reconstruction. This research addresses the study of system design of stereolithography process for object reconstruction, including reverse engineering and fossil reconstruction.

Of all reconstruction processes, collection of data is the first and most important step. Advanced three dimensional laser scanners provide an excellent technique to record the necessary shape information describing an object without damaging it. Results from the scanning is edited and revised by using different software packages to produce an acceptable .stl file for the stereolithography apparatus

(SLA machine). The SLA machine can then build an SLA duplicate of the object with high accuracy, and save time in manufacturing.

1.1 Motivation and Background

The keen competition in the global marketplace is encouraging industry to invent new methods to design and manufacture products. Surface roughness and dimensional accuracy are the key components for the manufacturing process. Both of these features should be well controlled to fulfill requirements of design and meet customers' needs. Concepts of cost effectiveness and time efficiency are also introduced to manufacturing engineers.

The traditional reconstruction or reproduction process depends on the original, or preserved blueprints or drawings. However, something that is unique and natural, such as a fossil, does not have any background blueprints or drawings. Also, it is almost impossible to use traditional measuring tools to measure all the geometric details of biological objects like fossils for reconstruction.

Progress in the technology of manufacturing is achieved by rapid prototyping and stereolithography. The real benefit of rapid prototyping is the enhanced visualization and tactile capability. It allows people to view and feel the scaled three dimensional images of products, instead of discussing two dimensional drawings. The stereolithography can quickly produce prototype parts directly from three dimensional CAD models to finished parts. It also prevents from print errors and inadequate machining using traditional methods. On the other hand, the development of software has increased the applications of rapid prototyping, and the collaboration of various software allows industry to create links between different machines for reconstruction.

Thanks to the cooperation of the Smithsonian Institution and the Advanced Design and Manufacturing Laboratory (ADML), a three-dimensional laser scanner, at the Smithsonian Institution, was used in this study to generate the object data for several reconstructions. Using different software, the data generated from scanning can be edited and transformed into .stl format files for the final models in the SLA machine housed in the ADML.

1.2 Scope of Thesis Research

One of the major objectives of this research is to design a rapid prototyping system for object reconstruction by using the stereolithography process. Research efforts are focused on the analysis of the calibration between hardware and software, and the techniques for object scanning. Development of a new rapid prototyping system will describe the whole process of reconstruction and the new system should use compatible machines and CAD software to save time of redesign. The scanning techniques document various approaches for data collection by laser scanning. The result of this research should lead to a mature system model which can be applied to other objects, and a more efficient and accurate prototyping process for manufacturing in general.

1.3 Organization of Thesis

The next five chapters of this thesis describe the constituents of this research. The contents of each chapter are summarized as follows:

Chapter Two: Literature Review

This chapter gives an overview of work relevant to this research. Descriptions of technical terms often used in the research are also provided for explanations of the problems encountered in this field.

Chapter Three: System Design for Object Reconstruction

This chapter presents the development of a new digital reconstruction process to save time and improve accuracy.

Chapter Four: Case Study I: Object Reconstruction of Fossils

The skull fossils, provided by the Smithsonian Institution, are one set of case study objects to be reconstructed, using different scanning techniques. The results of the digital reconstruction will be built as a physical model using stereolithography.

Chapter Five: Case Study II: Object Reconstruction of a Distributor

A second case study in object reconstruction, using a distributor casing of a truck, is presented as an example of reverse engineering. The main job is to manufacture an SLA duplicate of the distributor.

Chapter Six: Conclusions and Future Work

This chapter summarizes this research work and gives suggestions for future work in this field.

Chapter 2

Literature Review

2.1 Introduction

This chapter presents a background review of the literature pertaining to the research subjects related to this research work. Rapid prototyping has developed various system using different manufacturing techniques to produce prototypes and models for industry. Stereolithography, one of the rapid prototyping techniques, is utilized for the building of duplicates in the system design of this research. To evaluate the system design, two case studies are conducted to manufacture SLA duplicates of the scanned specimens. The first case study involves fossil reconstruction by using laser scanning, image processing and building by the stereolithography process. Using the same manufacturing process, the other case study builds an SLA duplicate of a part through reverse engineering. The review is provided in the following four sections. It covers the introduction of rapid prototyping, stereolithography process, fossil reconstruction and reverse engineering techniques.

2.2 Rapid Prototyping

Due to rapid development of computers and information technology in the late 1980s, rapid prototyping has emerged as a new and rapid developing technology to make prototypes. Rapid prototyping is already widely accepted in industry as a way to produce models, prototypes and tools. This technology is applied to numerous aspects of manufacturing because it can save time and produce accurate prototypes.

Like any new process, rapid prototyping took some time to be developed and finally accepted by industry. In the late 1970s and the early 1980s, the concepts of rapid prototyping were based on selectively curing a surface layer of photopolymer resin and building three dimensional objects layer by layer. From late 1986 through late 1987, many of today's rapid prototyping concepts were developed. Currently, rapid prototyping has developed a diversity of technologies because of the advancement of Ultraviolet (UV) lasers, new materials and software. Nowadays, rapid prototyping is not only benefiting prototype building, but it is being used in the final production of tools or products [Jacobs 1992].

Rapid prototyping systems are based on a layering process, either layer-additive or layer-subtractive. Layer-additive techniques attach a new layer to previously formed layers. Layer-subtractive techniques cut away unwanted sections from a full area layer of material. Various rapid prototyping systems may use a UV or CO_2 laser, and operate on either a point-by-point basis or an entire layer at a time. In the rapid prototyping systems marketplace, various rapid prototyping systems implement one of the five main technologies, such as Stereolithography, Laminated Object Manufacturing, Selective Laser Sintering, Fused Deposition Modeling and Solid Ground Curing. However, there are some new techniques for rapid prototyping under development, for example: Three-dimensional Printing, Shape Melting, Ballistic Particle Deposition and Selective Spray Metal Deposition [Jacobs 1996].

The stereolithography process is presented more detail in the next section, 2.3, and the characteristics of the other four main rapid prototyping technologies will be described:

•Laminated Object Manufacturing (LOM)

The LOM process, as the name implies, builds objects in thin layers of laminated sheet material and layers are joined by using a thermal adhesive. A .stl file is necessarily created for LOM process, then it is sliced at a thickness identical to that of the sheet material. The material is positioned in the work area continuously from a feed roller. Beneath the material, a computer-controlled platform is lowered as each layer is formed. Each cross-section of LOM parts is cut using a CO_2 laser. The CO_2 laser beam is delivered to the desired location via an XY scanning system that also contains the final focusing optics. A heated roller is also located above the material to activate the adhesive required to bond consecutive layers. An advantage of this process is that the surrounding unwanted material forms a natural support for the part. In summary, LOM is a layer-subtractive process which builds parts by laminating and laser-cutting the material in sheet form [Jacobs 1996, 1992].

•Selective Laser Sintering (SLS)

The SLS process generates three dimensional parts by sintering small thermoplastic particles with a high-power CO_2 laser beam. SLS produces objects from a CAD data base, and .stl files are acceptable. A thin layer of thermoplastic powder is evenly spread over the working area, which is a piston within a cylinder, by a roller. The part building chamber is purged with inert gas and heated to avoid oxygen contamination of the bonding surface, to prevent potential combustion or explosion, and to minimize the laser energy by raising the temperature of the uppermost layers of powder to just below the fusing point. A CO_2 laser beam is directed and focused onto the working area and the laser heat causes particles to fuse and bind to form a solid object. Each layer formed isolates within the unsintered powder of that layer. After a SLS part is finished, it is imbedded within a large loose powder cake. A potential advantage of SLS technology is that the powder surrounding the object serves as a support and it is later removed. Another advantage is the ability to sinter a wide variety of materials. In summation, SLS process is layer-additive and done on a point-by-point basis [Jacobs 1996, 1992].

•Fused Deposition Modeling (FDM)

The FDM process uses thermoplastic wire-like filaments as the material for part building. The material is melted in the delivery head then extruded from the nozzle in the form of a thin ribbon, and deposited in computer-controlled locations on a layer-by-layer basis. The part is built on a computer-controlled piston which is lowered to make room for the next layer. Layer thickness is determined by the material's characteristic, filament delivery speed, extrusion pressure, and the dimensions of the nozzle exit. It is important to maintain the thermoplastic filament temperature just above the solidification point and the previously formed layer must be maintained just below the solidification point to assure good adhesion between layers. An advantage of the FDM process is that a wide variety of thermoplastic filaments may be used. Further, the delivery process is on-demand. FDM is a layer-additive, non-laser, point-by-point building process [Jacobs 1996, 1992].

•Solid Ground Curing (SGC)

In the SGC approach, each layer of the part is generated by a multi-step process. The SGC technique uses photopolymer resins but does not implement a laser. The process begins with a CAD model of the desired object, in files of STL, VDA-FS or CFL format for production. All files are automatically converted to the CFL format. The CFL file provides the necessary cross-section data for each layer and is used to produce masks. A thin layer of liquid resin is spread on a carriage then exposed to a UV laser through a patterned mask which is a glass plate covered with black toner over the image of the cross-section. The UV radiation passing through transparent areas solidifies the resin and the remaining uncured resin, still liquid, is removed and replaced by wax. Both resin and wax are milled to a uniform thickness, forming a flat surface for the next layer. Finally, the part is imbedded within a solid block of wax. Throughout this operation, the carriage moves the on-building structure horizontally from station to station and lowers to accommodate new layers. The SGC technology is well suited for very large parts. It is a layer-additive, non-laser building process [Jacobs 1996,1992].

2.3 Stereolithography Process

Stereolithography was the first available layer-additive process to generate physical products for the rapid prototyping industry. The stereolithography process starts with the generation of a CAD model of the desired object. Then the surfaces of the CAD model are converted as a connected array of triangles, which may be as large or as small as desired [Jacobs 1996].

The software generates a series of triangular descriptions known as a .stl file which contains the X, Y, and Z coordinates of the three vertices of each triangle, as well as an index describing the orientation of the surface normal. The .stl file has become the standard of rapid prototyping industry, and is supported by more than forty CAD environment suppliers. After the generation of a .stl file, software slices the file to result in an SLI file, which represents a series of closely spaced two dimensional cross-sections of the three dimensional object.

Stereolithography utilizes a helium-cadmium laser or argon-ion laser to trace a liquid photopolymer. The object is built one layer at a time by using the laser to trace the layer structure on the surface of the photopolymer resin, which lies in a vat. When the laser exposure exceeds a threshold value, the photopolymer resin will transform to the solid phase. The focused laser is positioned by the scanning mirrors, which deflect the laser beam downward onto the surface of photopolymer. First, the laser beam traces the boundaries of the particular slice cross-section being traced. Once the borders have been completed, the laser solidifies the cross-section. The tracing speed is automatically adjusted so that the power level is enough to solidify the resin to the desired cure depth. Figure 2-1 illustrates the building facilities of the SLA-250/40 used in this study.

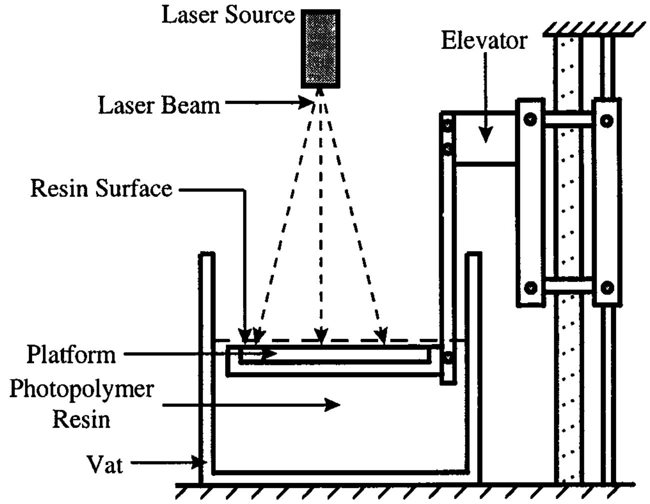


Figure 2-1 Building Facilities of the SLA-250/40.

The building process begins with fabricating a series of supports which hold the object in place during the build process. The first layer is attached to a platform positioned slightly beneath the surface of photopolymer resin. After the first layer is completed, the platform holding the object is lowered by a computer-controlled precision stepper motor. Fresh liquid resin coats over the last solidified layer and excess resin is removed with a recoater blade. The platform is then positioned so that the next resin level is cured at the correct thickness above the previously cured layer. The process is repeated until the entire physical object has been generated, from the bottom to the top. When the final layer has been completed, the platform is elevated and the whole object, including supports, emerges from the vat of liquid resin. After draining the excess resin, the platform, on which the object and its supports are built on, is taken out from the stereolithography apparatus. Uncured residual liquid resin is washed off the part, and the supports are then removed. Finally, the object is placed in a postcure apparatus to achieve full resin strength [Jacobs 1992].

2.4 Fossil Reconstruction

Reconstructing fossils through the stereolithography process differs radically from the traditional object-reconstruction process of manufacturing. In the traditional process, models are rebuilt from the blueprints or drawings of the objects. Fossil reconstruction, on the other hand, often involves reconstructing broken pieces from an individual [Tattersall and Sawyer 1996]. Successful integration of imaging and rapid prototyping is the key to fossil reconstruction by stereolithography.

The traditional method of fossil reconstruction uses molds and cast to make a duplicate of each broken specimen. A complete fossil can be built by adding clay or plaster sections to fill out the missing areas. The shape of these missing areas is usually modeled by hand. Scientists spend a long time making cast duplicates and reconstructing the incomplete ones, mostly by visual inspection. Duplicates are made by molding but the surfaces of fossils may be easily damaged and the mold lines are left on the duplicates. The traditional fossil reconstruction work is thus conducted visually without using computers and software for evaluation and reconstruction.

Nowadays, laser, CT or MRI scanning devices are employed to collect the surface data of an object for reconstruction and CAD software is utilized to inspect the image model for reconstruction on screen before the final building process [Zollikofer et al. 1995]. Missing parts and broken surfaces may be generated by using CAD software to construct a more complete model. The development of rapid prototyping makes the reconstruction work quick and accurate. The CAD file can be converted to a .stl file for one of the rapid prototyping systems. Another advantage is that the digital surface data of a specimen can also be used for other purposes, such as statistical studies to compare different species.

2.5 Reverse Engineering

Reverse engineering is the process of systematic evaluation of a product for the purpose of replication. Reverse engineering is usually implemented when old products for which there are no blueprints, especially those products designed before CAD existed, need to be built. In some cases, such as product modification, design reuse or an undocumented product, manufacturing engineers can apply reverse engineering to conduct further design and engineering processes. Reverse engineering is also applied in mold building. Software makes reverse engineering practical because designers can modify and redesign the object on the screen, and build the object as a solid model. Software also helps simulate the manufacturing operations and conduct finite element analysis, as required [Aronson 1996].

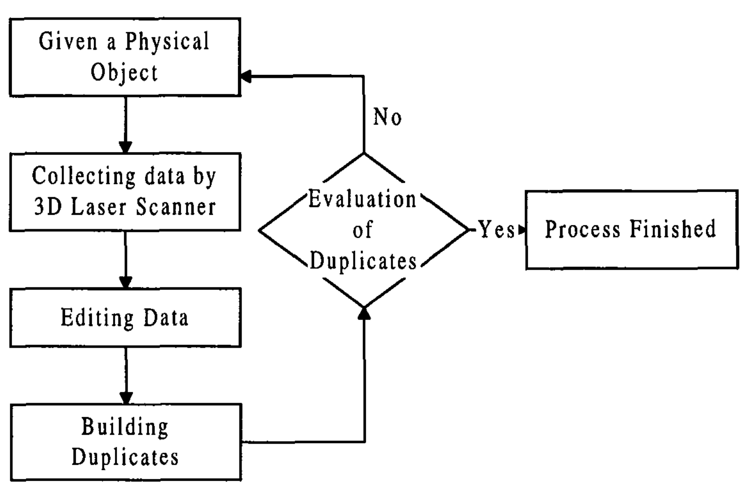
Reverse engineering is also the process used to create engineering data from existing parts by using traditional CMM machine, laser digitizer, caliper or micrometer measurements [Subbacharya 1991]. Seeing inside a part, however, is a special problem in reverse engineering because the mechanical and optical instruments only scan the surfaces of an object. There are two systems available to investigate the interior of an object. One system cuts a part to photograph the exposed inner surface and converts that layer to 2-D data. The other system uses an X-ray CT-scanner which operates much like a medical CT scanner to look inside parts with a complex internal geometry [Aronson 1996]. The engineering data may include the drawings and other special information so that the parts can be represented completely and accurately. An undocumented object needs to be measured to collect all of its dimensions for the preparation of new documentation. The data acquired from reverse engineering can be manipulated as new blueprints or drawings in CAD environments and the new documentation may be revised or redesigned for new product development.

Chapter 3

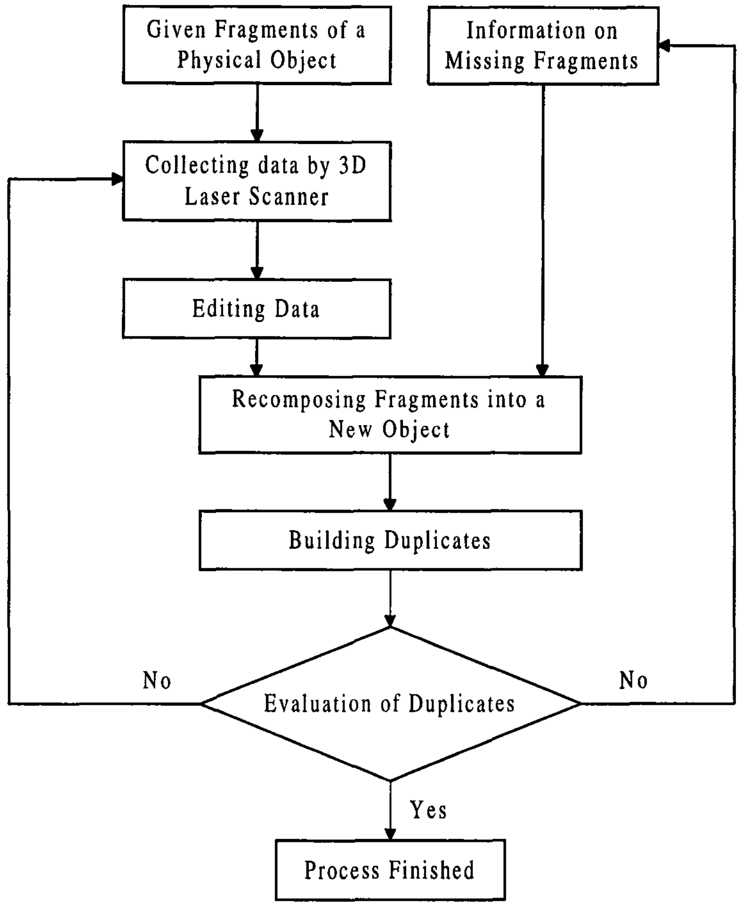
System Design for Object Reconstruction

3.1 Introduction

The focus of this research is to design a system for conducting object reconstruction. This chapter presents the system design for object reconstruction by using information-based manufacturing. The components of the system include hardware, a three-dimensional laser scanner and a stereolithography apparatus, and CAD software tools. Figure 3-1 illustrates the process of the system design for two different object sources by using flow charts. This chapter also includes a description of scanning techniques for capturing the geometry of objects to collect highly accurate data and save time in editing the scanning data. At the end of this chapter, a building process is presented to introduce the stages of this approach for object reconstruction.



(a) Process of system for a complete object.



(b) Process of system for the fragments of an object.

Figure 3-1 Processes of System Design of Research Work.

3.2 Situation Analysis

The absence of blueprints or drawings describing an object is a major barrier preventing mass reproduction. The first step in any reconstruction is gathering descriptive data on the product, either in diagram or measurements form. In this research, data collection relies on laser scanning, which is a form of optical measurement, instead of drawing or blueprint information. The new approach represents a major advance to overcome the absence of an "original design", as is always the case with natural objects.

There is a common scenario in manufacturing; The last part of an old model is left in the warehouse but there is no blueprint or drawing saved for the part. Meanwhile, there are continuous orders of the part from customers. In traditional manufacturing, the reproduction work starts from the blueprint to build a model. However, in this case, the reproduction work cannot be done because of the absence of a blueprint. With reverse engineering, this difficulty, drawing a new blueprint for the part, can be overcome by using a digitizer or series of manual measurements. Furthermore, there is a shortcut to avoid redrawing the blueprint by using a system which can transfer the data directly into the format for building. After this process a model of the part can be generated quickly.

Apart from industry, a similar situation can easily occur in other research fields. For example, in archeology or paleontology, a natural fossil fragment of an animal, or an artifact, is discovered. Not only is it unique, but its complicated geometry is also a big challenge for handling. In order to protect the completeness of the fossil, a duplicate is needed for the subsequent research, and even more duplicates are necessary to provide to other research groups. Obviously, a natural fossil is made without blueprints or designs. The complicated geometry of the fossil makes it impossible to collect a description of the surface by manual measurement and that makes the drawing of blueprint more difficult or even impossible.

In both of the previous two cases, reproduction or reconstruction is required without the availability of blueprints. Traditional manufacturing processes require the dimensions of an object to start the building process. Under the preceding conditions, object reconstruction can not be achieved using traditional processes. Therefore, a new manufacturing process must be developed to replace the traditional one. In this research, two case studies based on those situations are provided to evaluate the system design for object reconstruction.

3.3 System Design for Object Reconstruction

The system for conducting the research work is composed of two machines, a stereolithography apparatus and a three-dimensional laser scanner, and three software tools, Maestro, DataSculpt and Magics RP. All components of the system are presented in the following sections.

3.3.1 Stereolithography Apparatus, SLA-250/40

SLA-250/40 (Figure 3-2) is a product of 3D Systems, Inc. The major components of the SLA-250/40 are: a laser, an optical system, a process chamber, a vat, a control panel and a desktop computer (controller). The SLA software is installed on the controller prior to shipping. It is a computer-controlled, electro-mechanical, scanning laser machine designed to trace the cross-sections of an object on the surface of a liquid photopolymer stored in the vat.

The SLA-250 uses a helium-cadmium laser under computer control which is a single tube design. The optical system in the SLA-250 is composed of a shutter assembly, three beam-turning mirrors, a beam expander, and X-Y dynamic mirrors mounted on an optics plate above the process chamber. The process chamber includes a platform, an elevator, a heater, a resin vat and beam profilers. The SLA-250 resin vat provides a space up to 250 mm x 250 mm x 250 mm. The controller controls all of the stereolithography processes, which include the functions such as slice and verify the building files.

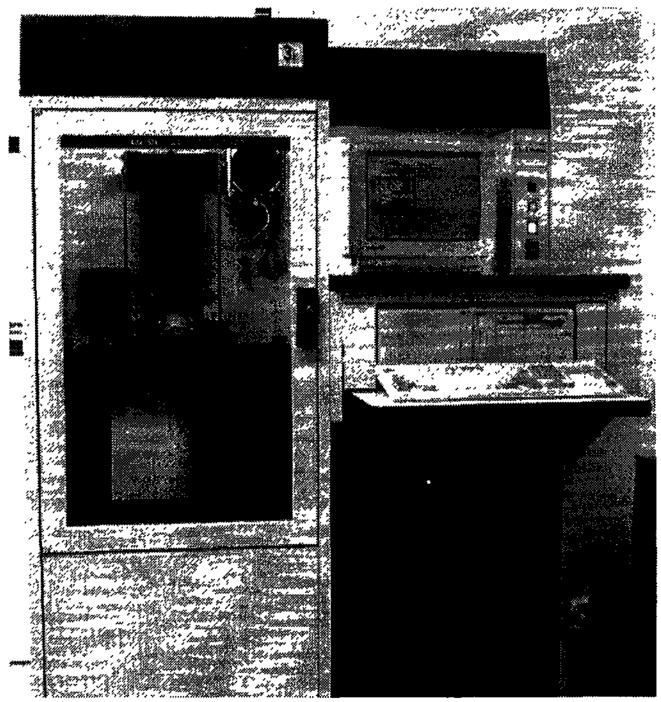


Figure 3-2 Stereolithography Apparatus, SLA-250/40.

The software on the controller runs on MS-DOS and software options are selected from pull-down menus by pressing the desired number on the keyboard or by using arrow keys to highlight the option. Commands are listed in the order normally associated with part building. The SLA-250 allows resin changes and specifying different resin parameters.

3.3.2 Three-Dimensional Laser Scanner, Surveyor 3000

Surveyor 3000 (Figure 3-3) is a laser scanner manufactured by Laser Design, Inc. The laser scanner uses a triangulation based sensor that projects a small spot of laser light onto the surface of an object being digitized. A laser sensor and object platform are arranged as a three-axes computer controlled positioning system. An object which is to be digitized is either placed on the platform and moved in a plane or glued on a shaft horizontally and rotated. The laser sensor lies above it. The three dimensional coordinate locations of the object's surface are collected by the digitizing system according to scanning density and pattern parameters set by the user.

The laser scanner emits a small spot laser onto the surface of an object and a two dimensional CCD (Charge Coupled Device) array views the spot and determines where the center of the spot is located on the array. This location, along with the computer controlled machine axis positions, is used to compute the coordinate of the laser spot on the surface of the object. In order to let the reflected laser spot fall on the surface of the CCD array , the surface of the object must be at least a minimum distance away. Therefore, during scanning, the object is kept within the range of the laser. Should the surface geometry of the object change abruptly, the laser scanner will automatically stop and execute an up or down search procedure to find the surface again. Surveyor 3000 is equipped with a work envelope of 15.7" x 23.5" x 11.8" for object digitizing.

It is important to process the resultant scanning data to the viability of using such high density information. Laser Design, Inc. has developed a proprietary software package, DataSculpt, for its laser scanner to translate the complex three dimensional data into an applied form, .stl format.

Figure 3-3 Three-Dimensional Laser Scanner, Surveyor 3000.

3.3.3 Maestro

Maestro was developed by 3D Systems, Inc. and it is the integration of six essential software Modules: Part Manager, View, 3dverify, CSlice, Converge, and Vista. Maestro includes four major steps to convert surfaces or solid models into a set of files for the building process in a stereolithography apparatus.

The first step is verification of the .stl file. After the .stl files have been loaded into Maestro, the user can analyze and correct corrupt .stl files by using 3dverify. Examples of flaws that can be identified and fixed are: gaps between triangles, overlapping triangles, redundant triangles, and incorrect normal directions. After verification is finished, 3dverify can output an analysis report (.vmf file), and a .stl image (.vtl file), or a replacement .stl file that overwrites the original .stl file.

The second step is focused on the orientation and placement of the part for best construction within the work envelope. The View module allows visual inspection of files and provides the ability to manipulate the object file into position for preparation and building by all axis translation, rotation and scaling. With these functions, a user is able to locate several individual components relative to each other and design the building envelope without the need for a CAD program. The View program also enables users to copy one or more component files.

The third step concentrates on generating supports for the part through Vista, which is used to create supports for CAD created .stl files. The Vista module has a graphical user interface which allows users to visually inspect the supports and the part. Through the interface, a user can modify, edit, delete, or add supports by a combination of mouse and keyboard actions.

The final step is to prepare building files. It involves selecting build and recoat styles, slicing, creation of build files, and the selection of resin shrink. CSlice and Converge form a single user interface to convert the CAD object files, build style files and recoat files, into build files for use in the stereolithography apparatus. The build files for the SLA-250 machine are the .l(layer), .prm(parameter), .r(range), .v(vector) files.

3.3.4 DataSculpt

DataSculpt, three-dimensional scanning data editing software developed by Laser Design, Inc., is a workstation and PC-based software package that provides a graphic and interactive interface to utilize the scanning data in the real world. It can manually or automatically process high- or low-density, 2D or 3D coordinate point data. The software recognizes and reduces the data so that it is immediately useful with the user's computer-based CAD or CAM system.

DataSculpt also provides instructions directly to a computer controlled machining center to carve the shape scanned into steel for the purpose of creating a mold or die for manufacturing the part or shape into a variety of materials. It also has direct output to stereolithography devices for three dimensional solid representation of modified scanned object. This function to translate the raw scan data into an applied form brings specific solutions to reverse engineering problems.

DataSculpt is the proprietary editing software for Surveyor 3000. After a scanning file loaded into DataSculpt, a user can edit the scanning vertexes and polylines through using a variety of CAD-like features such as merge, blend, delete and close etc. The final edited scanning file can be converted into a mesh (.msh) file first then translated into a .stl file. A user can visually inspect the mesh file with rendering and other visualization features.

3.3.5 Magics RP

Magics RP is developed by Materialise Co. and it is available on Windows '95, and Silicon Graphics. The RP stands for Rapid Prototyping. It is a three-dimensional viewing CAD software and has four viewing modes: flat shade, shade with wire frame, wire frame, and triangle view. Magics RP has real time visualization and measurements with on line feature recognition such as point to point, point to line, and point to center of an arc.

The software, Magics RP, has advanced manipulations: rescale, mirror, translate, alignment of .stl files, and bottom plane. It also can fix .stl files by automatically repairing flipped normals, closing gaps in the .stl files, removing bad triangles, and manual editing. Punching holes helps users to overcome trapped volume problems. The Boolean operations can add, subtract, or unite one .stl file to another .stl file. The build time calculation is able to optimize machine productivity. Magics RP has a function of cutting of .stl files, and non-straight cutting profiles.

3.4 Scanning Techniques

The three-dimensional laser scanner, Surveyor 3000, provides two different scanning designs including flat scanning and rotational scanning. To scan an object, Surveyor 3000 may move the specimen along the X- or Y-axes or rotate it along the

A-axis. The laser head moves up and down along the Z-axis to focus. Figure 3-4 is a picture to show the defined axes of Surveyor 3000. Actually, in all of the scanning techniques, the laser head always stays in the same x and y coordinates, and only moves up and down along the Z-axis. In a front view, the A-axis is parallel to the X-axis, through the center of the dowel affixed to the A-stage. During rotational scanning, rotation around the A-axis replaces the linear movement along the Y-axis. The position of a point in x, y or z is determined by the machine directly from the position where the laser is fired and focused.

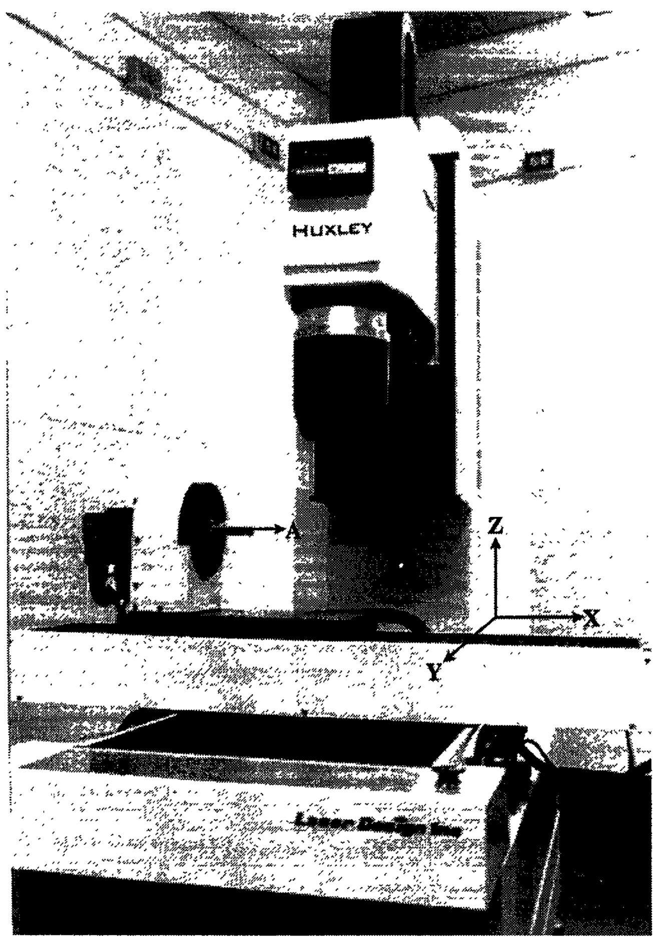


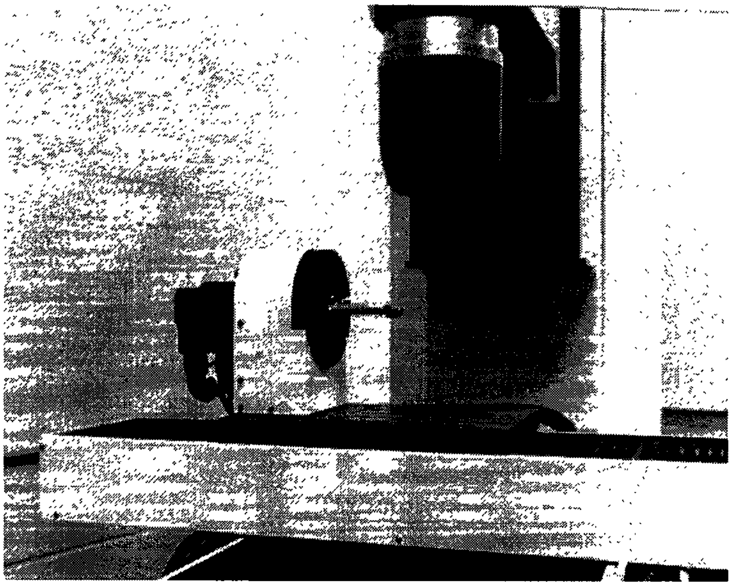
Figure 3-4 The Axes of the Surveyor 3000.

3.4.1 Flat Scanning

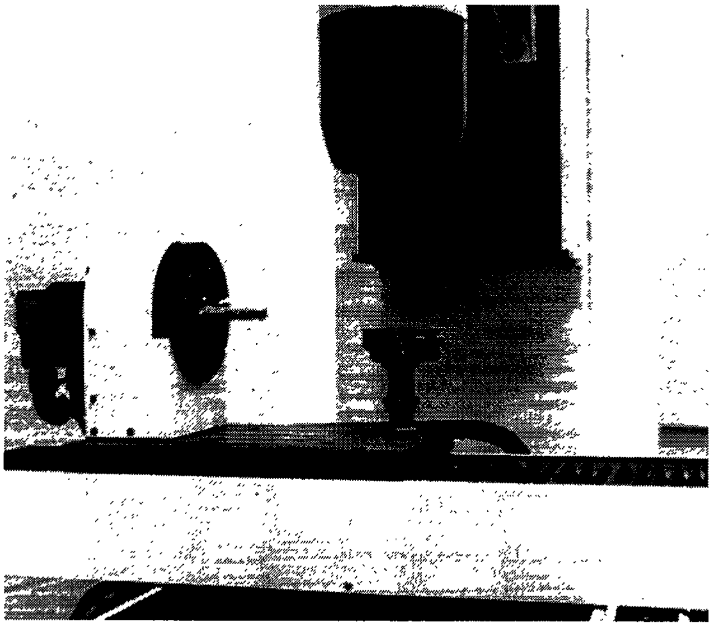
In an approach to collect data describing the surface of an object, a user can create a flat scanning window of the specimen, instructing the machine to record the object surface contained within the window. A combination of flat scanning at various angles may form the whole surface of an object. However, the flat scanning data collected at different angles is saved as separate layers, which must be combined and edited extensively to create a single complete object.

In flat scanning, the machinery holding the object moves along the X- and Y-axes and the laser head searches up and down to focus. The specimen may be attached on the platform or to the A stage (Figure 3-5). The hot glue is used to mount most of objects. If only one surface of a specimen needs to be scanned, the object can be glued to the platform in order to reduce vibrations. To collect various surfaces of an object at various angles, the specimen must be attached to the A-axis by using a shaft through the dowel.

For multiple flat scanning of an object, the various flat scanning windows at various angles must be set up before the whole scanning process starts. In a flat scanning widow, the machinery holding an object moves on the X-Y plane only; it will not rotate to different angles until a scanning window has been finished. With the multiple flat scanning process, an object is fixed then rotated to the next scanning window set at a different angle. The increments of the X- and Y-axes and the density of data points can be input as desired before scanning. The machinery moves along the Y-axis to scan the object first to complete one pass over it, then moves a unit increment along the X-axis to position the laser for the next pass. This scanning order repeats until a scanning widow has been finished.



(a) A specimen attached to the shaft for flat scanning.



(b) A specimen attached to the platform for flat scanning.

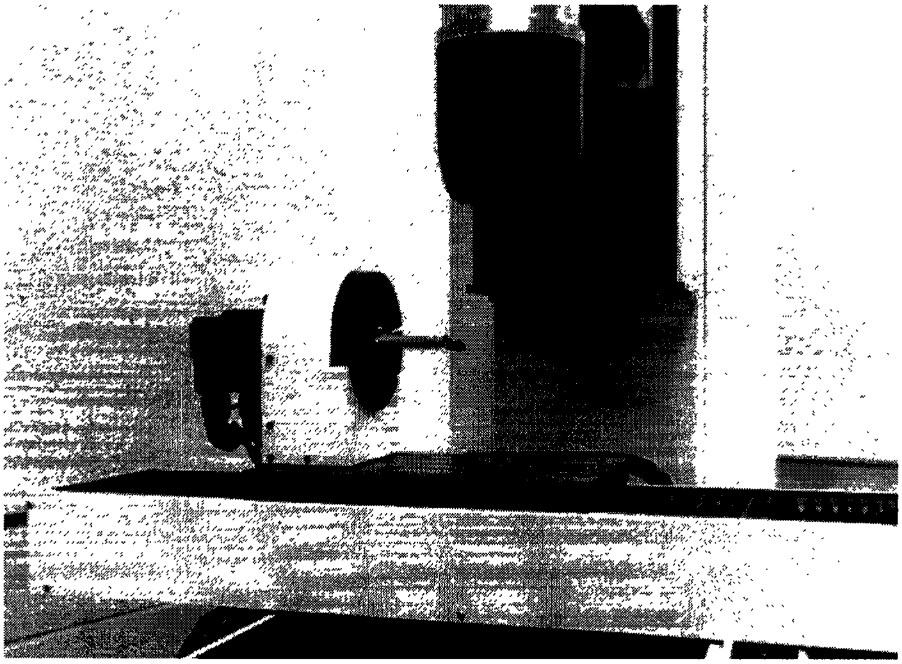
Figure 3-5 The Preparation for Flat Scanning.

Flat scanning is a good approach to scan an object which is less concave or free of cavities. Multiple flat scanning windows of different angles can avoid much overshadowing and they may give as much or more information than a single flat or rotational scanning. In most of cases, flat scanning is recommended when a single scanning widow can cover most of the necessary information, or an object has random geometry.

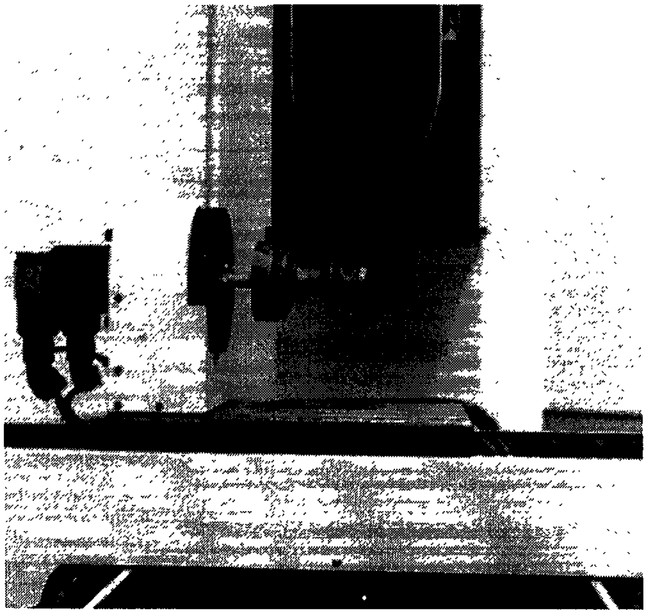
3.4.2 Rotational Scanning

Rotational scanning is the other scanning approach provided by Surveyor 3000 to rotate and scan an object along the A-axis. To collect all surface data of an object, rotational scanning is efficient because only one rotational scanning window can replace multiple, flat scanning windows. The angle of rotation along the A-axis can be set as desired, from 0° to 360°, so the rotation does not have to be at exact 360° circle.

In rotational scanning, the shaft holding the specimen is through the center of a dowel and parallel to the A-axis. The specimen may be attached on the shaft or the shaft may go through the specimen. Figure 3-6 shows the preparation for rotational scanning. If an object is heavy, the shaft has to be fixed tightly by screws or glue to prevent the sliding of the shaft with the object, and the heavy one needs to be attached on the shaft strongly as well. Either sliding out of, or around the dowel, will corrupt the scanning data.



(a) A specimen attached to the shaft for rotational scanning.



(b) The shaft through a specimen for rotational scanning.

Figure 3-6 The Preparation for Rotational Scanning.

To conduct rotational scanning, the machinery holding the specimen moves along the X-axis only, which means the coordinate of y is unchanged as the object rotates around the A-axis. The machinery does not move along the Y-axis because the rotation replaces movement in the Y-axis. For rotational scanning, an object can be scanned at different point density for various sections. Point density is the distance between two adjacent lines and the angle of two adjacent points. The increment of movement along the X-axis and rotational angle can be set as need before scanning. During rotational scanning, the machinery rotates along the A-axis first to scan an object until a rotational loop is scanned, then the machinery moves along the X-axis in increments set for the window. This sequence, rotation first then translations, continues until the whole object is scanned.

Rotation scanning is mostly utilized for an object which is symmetric or cylindrical. In rotational scanning, however, overshadowing and concavities can still cause loss of surface data. However, it is easier and quicker to edit rotational scanning data than the data acquired from multiple flat scanning windows. It is efficient and easy to use rotational scanning to scan a cylindrical object.

3.4.3 Combined Scanning

Both flat scanning and rotational scanning have their own advantages and disadvantages for data collection and editing. It is necessary to develop a new scanning technique to reduce the effect of overshadowing, but also to save the time needed for editing. The combination of flat scanning and rotational scanning, called combined scanning, provides a feasible way to collect as much or more information than needed, and shortens the time to prepare scanning data for the building in the

SLA machine. Obviously, the combined approach balances the advantages and disadvantages of the two techniques.

In order to combine flat scanning and rotational scanning, the specimen has to be attached to the shaft which is parallel to and rotates along the A-axis. The same is true for pure rotational scanning. The orientation of a specimen attached to the shaft must be carefully decided to reduce the effect of shadows caused by overshadowing and concavities. The rotational scanning has to be done first because the various angles of flat scanning windows are chosen from the output data of rotational scanning. After the rotational scanning is finished, flat scanning is implemented without removing the object from its mount.

The increment of the X-axis movement has to equal the line density of rotational scanning and all flat scanning windows in order to keep the movement along the X-axis consistent and preserve the same starting point for image processing. The line density must be the same in rotational and various flat scanning windows so that all the scanning polylines of each match up with one another at specific x coordinate. In combined scanning, the rotational scanning has to be conducted first, then the information of rotational scanning can be viewed in DataSculpt to decide the position needed for initiating the flat scanning. In each flat scanning window, the area to be scanned need not cover the whole object. It can be reduced to a minimal size to save scanning time, while still providing all necessary information. In most cases, multiple flat scanning windows are employed to cover all the details of a complex surface, such as holes, concavities and overshadowed areas. When all flat scanning windows are finished, the data is transferred into DataSculpt for editing.

Combined scanning is the best scanning technique for a complex object, especially one with many bumps and concave surfaces. However, it is necessary to blend all the layers into a single object. Using combined scanning, the data loss in rotational scanning may be supplied by multiple flat scanning. Because the increment of the X-axis movement is consistent and the line density is exactly the same in all scanning windows, the scanning polylines of different layers can still fit into the correct x-coordinates. And none of scanning polylines, the form in which point data is displayed as cross-sections, will fall between two adjacent ones.

3.5 Reconstruction Process

In this research, object reconstruction starts with data collection using the three-dimensional laser scanner, Surveyor 3000, housed in the Smithsonian Institution. It finishes with building the duplicate object in the stereolithography apparatus, SLA-250, housed in ADML, University of Maryland. A flow chart of the building process, including the file format, machinery and software is provided for illustration (Figure 3-7), followed by the details of the reconstruction process.

First, the object for reconstruction is scanned using the Surveyor 3000, employing the scanning approach required by its geometry and shape. If rotation is necessary, the object must be attached on the A-stage or a shaft through the dowel of the A stage. After scanning, the information is saved as .scn file which is edited in DataSculpt. Editing the scanning data is very time-consuming and tedious, but essential and unavoidable. The drop-off is caused by the laser beam missing the object and striking the platform, and the spikes contained in the scanning data are caused by the shiny surfaces of the object. All drop-off and spikes must be deleted and replaced by other data from different layers. When editing work is finished, the original scanning data is ready to be exported as a mesh file (.msh file). Before saving mesh files, it is important to render the object for observation. If there are any errors or discrepancies from the real object, each cross-section of the digital model has to be examined again.

The .msh file exported from the .scn file is transferred into a .stl file by using DataSculpt. If there are several .stl files to cover all features of a single object, all .stl files need to be merged into a single .stl file of the object by using Magics RP. After that, the .stl file is loaded into Maestro, which can be used to correct the holes or gaps and overwrite the former .stl file. If the duplicate needs to be scaled up or down, Maestro allows re-scaling of the X-, Y- or Z-axes. Maestro also creates supports automatically, which lift the duplicate from the platform in the SLA-250, for the .stl file. After generating supports, both of the .stl files for part and supports are sliced and transferred into four building files (.l, .prm, .r, and .v) for processing in the SLA-250.

To start building in the SLA-250, all the four files have to be loaded into the controller. The power of laser beam and the resin temperature have to meet the requirements of the building process. After checking the building environment and finishing a simulation, the duplicate is built. When finished, the platform holding the duplicate and its supports are taken out of the chamber for cleaning. All supports have to be removed carefully and gently, and the duplicate needs to be washed in alcohol. The uncured resin must be removed due to its toxicity and its effect on the dimensional accuracy of the part. The cleaned duplicate is put into a post-curing apparatus, using Ultraviolet. Finally, the duplicate of the part is manufactured and the whole reconstruction process is finished.

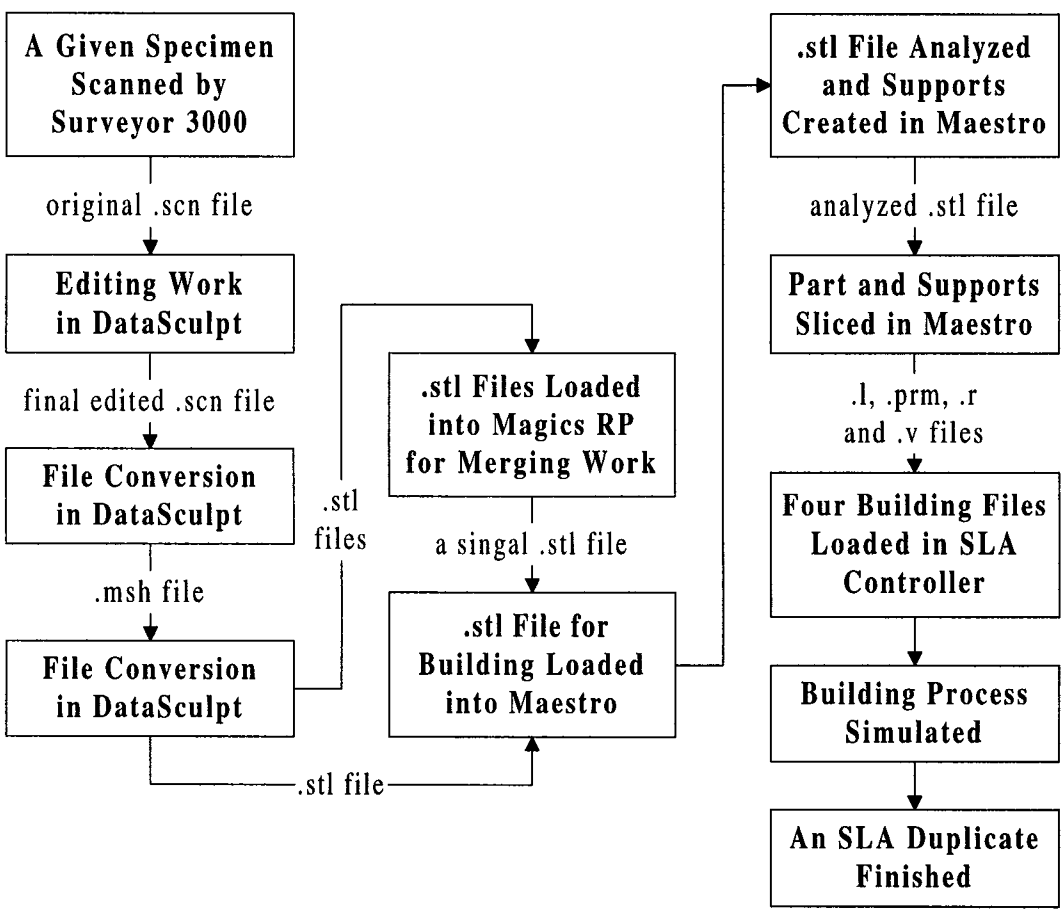


Figure 3-7 Flow Chart of the Reconstruction Process.

Chapter 4

Case Study I: Object Reconstruction of Fossils

4.1 Introduction

Five epoxy duplicates of *Homunculus* fossil fragments (Figure 4-1) were provided by the Department of Zoological Research, National Zoological Park of the Smithsonian Institution. These fossil fragment duplicates are of the left side of a crushed facial skull and a broken jaw. The facial skull is composed of a top face and a bottom face. The dimensions of the five duplicates are listed in Table 4-1. The real fossils were found in Rio Gallegos, Argentina in 1891. *Homunculus* has been extinct for about 17 million years. The epoxy duplicates were manufactured by Otto Simonis of the American Museum of Natural History in the1970s. Figure 4-2 shows pictures of the original fossil material in their condition before cleaning, preparation and casting. The actual fossils are curated in the Museo Argentino de Ciencias Naturales "Bernardino Rivadavia", in Buenos Aires, Argentina.

To reconstruct the fossil *Homunculus* is very meaningful in both paleontology and industry. The fossils of *Homunculus* have an important position in New World Monkey research because they were among the first monkey fossils found in South America. Until today, however, *Homunculus* has not been well located in the family tree. Hopefully, the reconstruction of these fossils can help paleontologists also learn more about the diet and living habits of *Homunculus* by examining the shape of its teeth and the size of the eye socket. For industry, if the reconstruction process is successful, it can help manufacturers develop approaches to rebuild many precious and fragile fossils and other museum materials.

	Maximum Length	Maximum Width	Maximum Height
Left Jaw	23.88	5.97	13.69
Right Jaw	44.56	8.40	22.85
Facial Skull	41.37	29.42	17.23
Top Face	28.08	16.76	21.13
Bottom Face	29.85	16.80	20.22

Unit: mm

Table 4-1 The Dimensions of the Epoxy Duplicates of *Homunculus*.

(a) Left: left jaw. Right: right jaw.

(b) Left: bottom face. Center: facial skull. Right: top face.

Figure 4-1 The Five Epoxy Duplicates of *Homunculus* for Reconstruction.

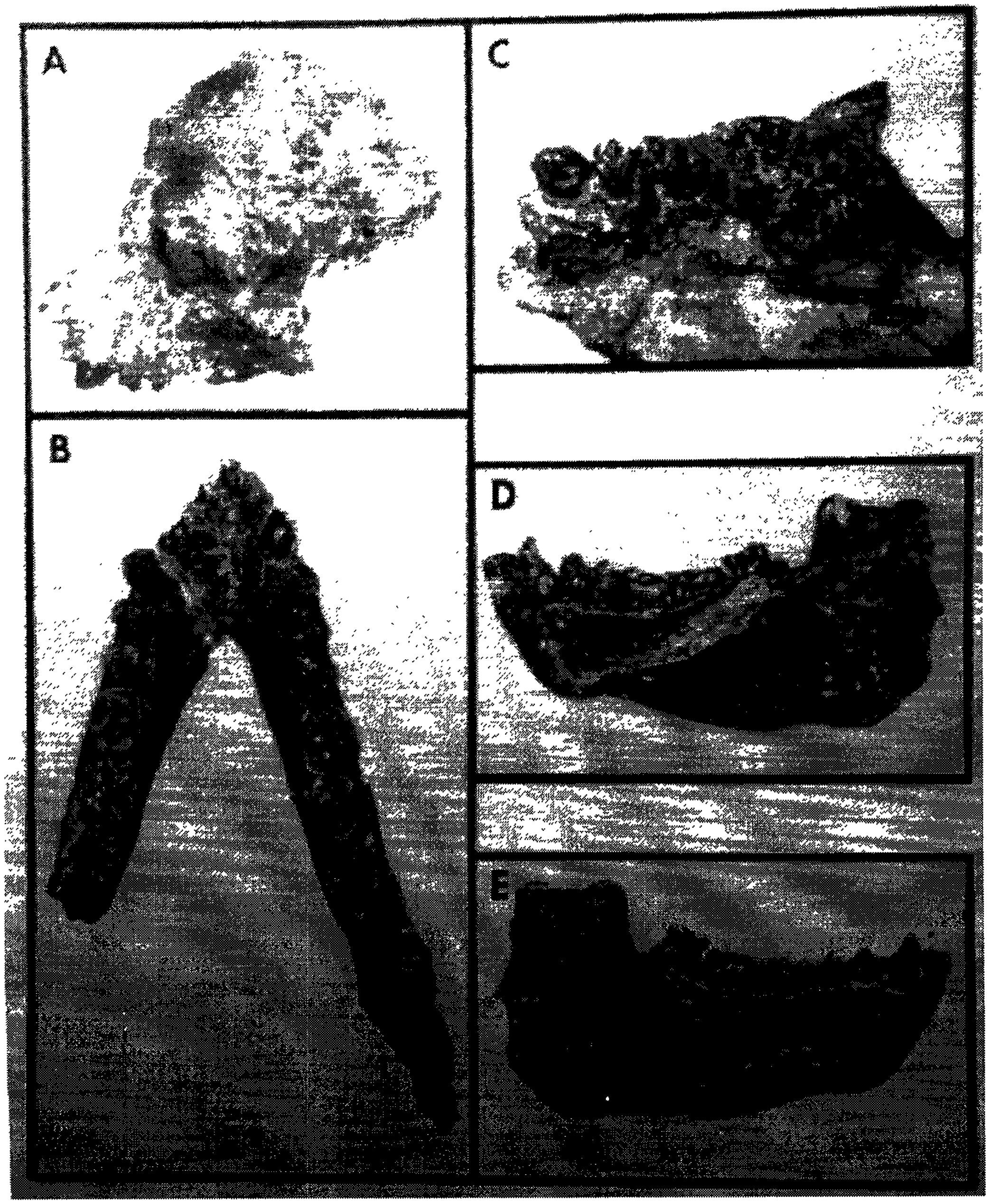


Figure 4-2 Original Fossils of *Homunculus* (F. Szalay & E. Delson, 1979).

There are several features to help the fossil reconstruction of *Homunculus* by using the only five available specimens. On front, the upper Premolar 2 tooth of the bottom face can match with the lower Premolar 2 tooth of jaw. On back, the upper Molar 3 tooth of bottom face should be right above the lower Molar 3 tooth of the jaw.

The orbit of *Homunculus* is composed of top face and bottom face, and it is a smooth sphere. The natural anatomical lines of the right jaw and the top face are preserved for reconstruction to be used as a midline for mirror images.

The goal in reconstructing these fossils is to rebuild the whole facial skull by using the scanning data of fragments, then build new duplicates of the fragments using an SLA machine. The advanced CAD environment can align, rotate and mirror the scanning information to reconstruct a new model of the skull. Using the new .stl file of each fossil fragment, the SLA can build new duplicates and maintain their accuracy.

4.2 The First Reconstruction Trial

In this research, the reconstruction of these fossils starts with laser scanning to generate the surface data needed for building an SLA model. Collecting a surface description of the object is the most critical step in the reconstruction process. There are three different scanning techniques which may be employed to scan the specimen, but in the first trials, only rotational scanning was used to scan the epoxy duplicates for surface data.

4.2.1 Fossil Scanning

Before starting to scan the fossils, the objects must be oriented for scanning and positioned properly in the scanning device. The orientation is important because good orientation can prevent or minimize the overshadowing of surface details within concavities, for example. Good orientation for scanning is also helpful to shorten the time of editing work involving the raw scanning data. The spot for attachment of the object has to be carefully chosen in order to collect as many features as possible. The glue used for attachment must rigidly support the specimen, but the amount of glue should be limited so that it does not cover the object. The scanning density of each scanned specimen used in this trial is provided in Table 4-2.

	Line Density	Point Density
Left Jaw	0.25 mm	5°
Right Jaw	0.25 mm	1°
Facial Skull	0.25 mm	1.2°

Table 4-2 The Scanning Density Used in the First Reconstruction Trial.

When the first trial reconstruction was conducted, the combined scanning had not been developed. Because parts of the fossils are a flat shape but have complex geometry, an approach using multiple flat scanning windows may collect most of the surface information. However, the editing work would become too tedious to finish, so only a single rotational scanning was employed to scan the objects. To avoid hiding features, the specimens are mounted at the rear end (Figure 4-3), where the specimens are naturally broken. The chance of odd spectral reflection, which causes spikes in the raw measurements data, can be reduced by coating the object with a light brushing of baby powder. A paper box is placed about one inch under the specimen to shorten the focus time needed by the laser head when it moves beyond the part itself during the course of scanning. Table 4-3 lists the scanning time used and number of points collected in this trial.

	Scanning Time	Number of Points
Left Jaw	1:07:30	45,780
Right Jaw	3:37:48	63,860
Facial Skull	22:47:54	6,853

Table 4-3 The Scanning Time Used and Number of Points Collected in the First Reconstruction Trial.

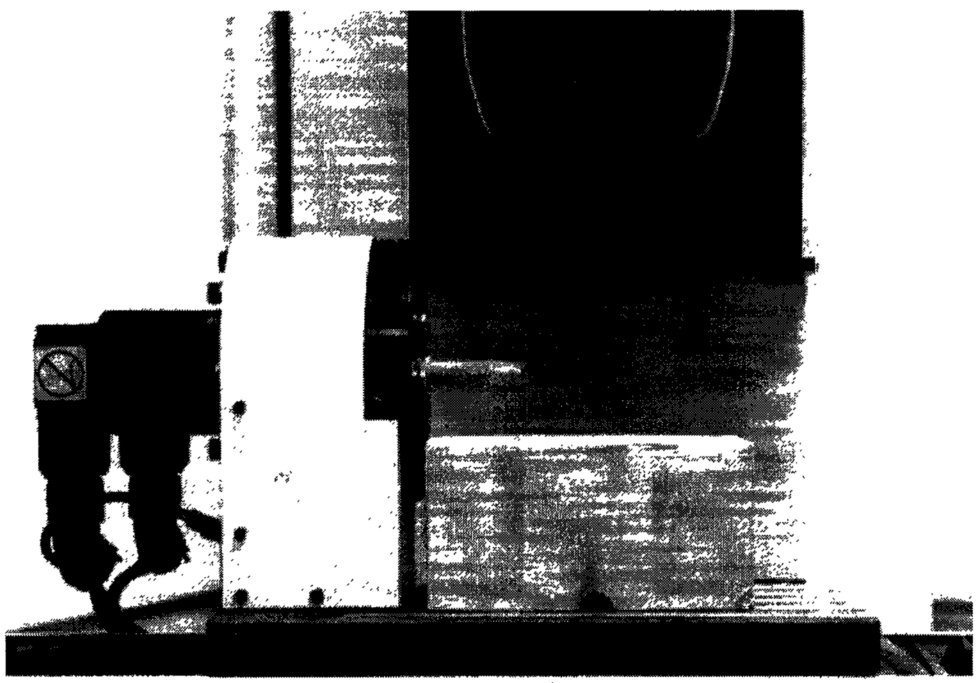
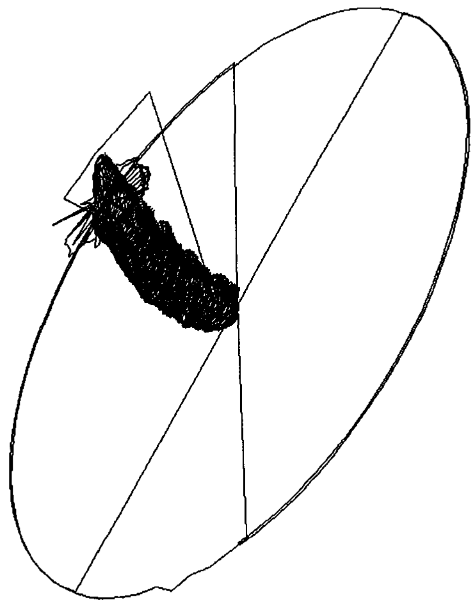


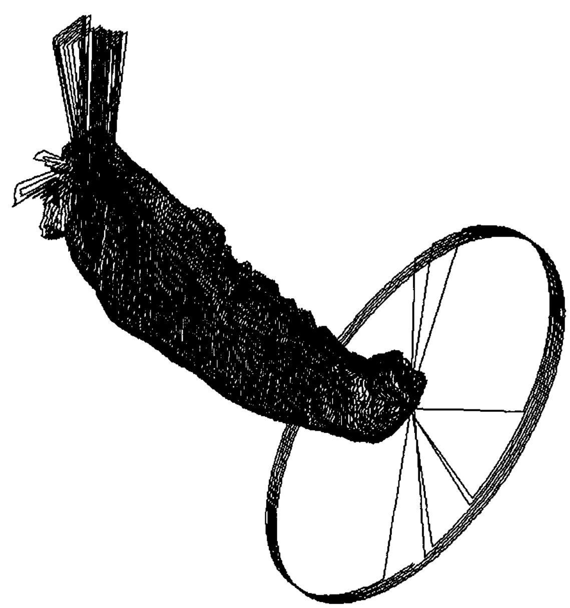
Figure 4-3 The Preparation for Scanning Work.

4.2.2 Data Editing

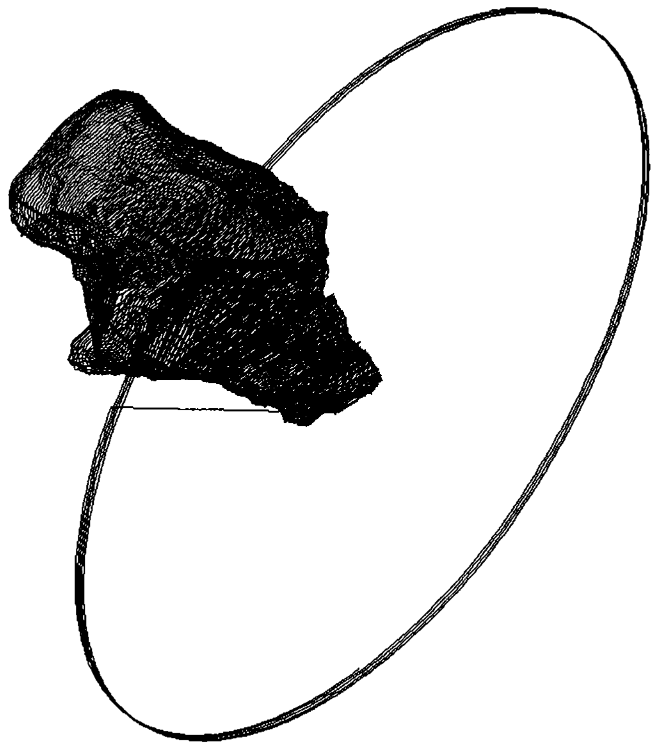
After the scanning of a specimen is finished, the raw scanning file (.scn file) is loaded into DataSculpt. Figure 4-4 shows the raw scanning polylines of three fossils in an isometric view. The original scanning polylines include the true surface data, the drop-offs to the paper box, and the spikes caused by shiny surface. The arcs which surround the real fossil polylines represent the surface of the paper box. Because the paper box does not rotate with the fossil and maintains the same z coordinate, the drop-off points of the same cross-section connect together to form an arc.



(a) Left jaw (Actual size: L:23.88mm, W:5.97mm, H:13.69mm).



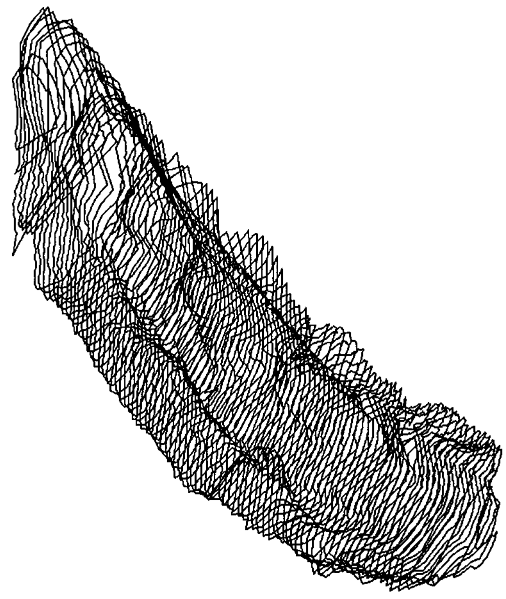
(b) Right jaw (Actual Size: L:44.56mm, W:8.40mm, H:22.85mm).



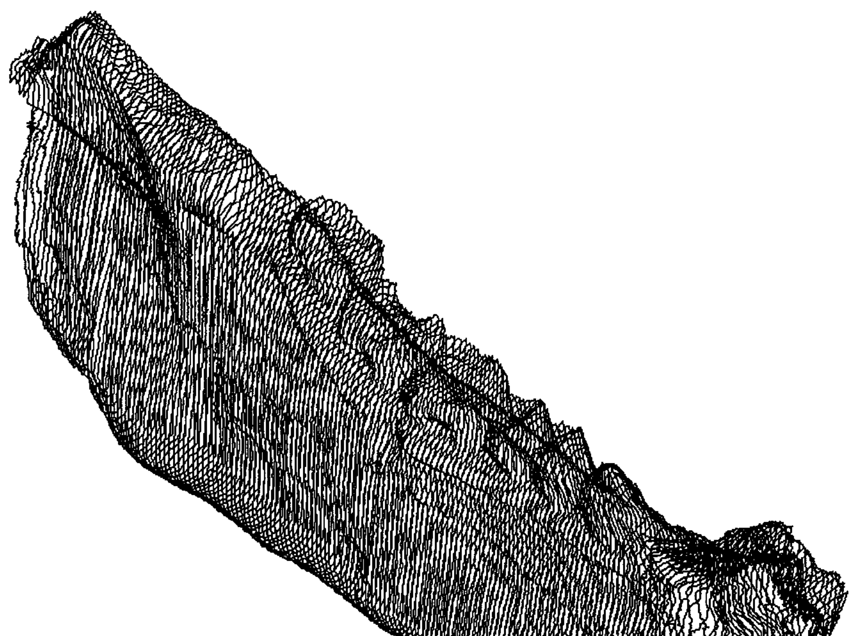
(c) Facial skull (Actual Size: L:41.37mm, W29.42mm, H:17.23mm).

Figure 4-4 Original Scanning Polylines of the First Reconstruction Trial.

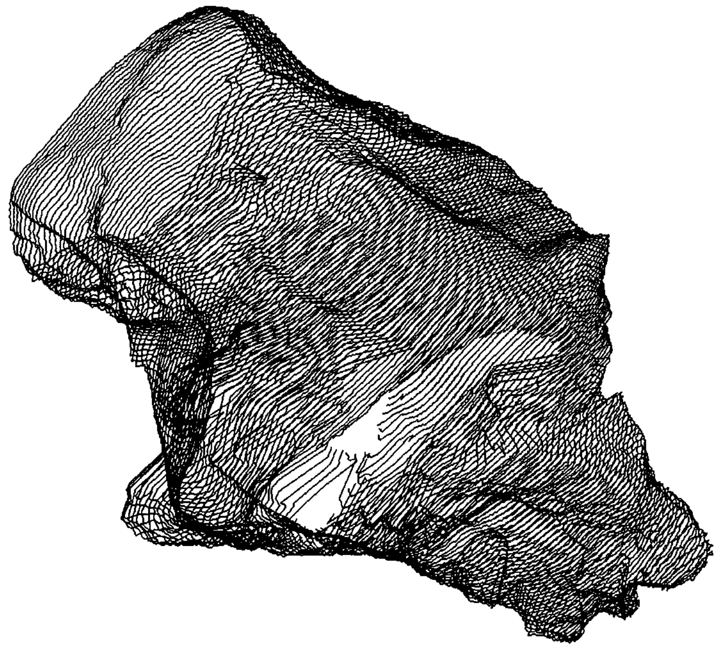
For convenience, the editing work needs to be done by inspecting cross-sections. The noise, including spikes and drop-offs, has to be deleted first, then each polyline (cross-section) has to be repaired. After deleting errors, a scanning polyline may be separated into several segments. Various editing functions, such as merge, blend, and close etc., may be utilized to connect those segments into a full cross-section which is to produce a more accurate image of the real surface of the fragment. Figures 4-5 represent the final edited scanning polylines in an isometric view. The .scn file is converted into a .msh file after finishing the editing work. Finally the .msh file is converted into a .stl file.



(a) Left jaw (Actual size: L:23.88mm, W:5.97mm, H:13.69mm).



(b) Right jaw (Actual Size: L:44.56mm, W:8.40mm, H:22.85mm).



(c) Facial skull (Actual size: L:41.37mm, W:29.42mm, H:17.23mm).

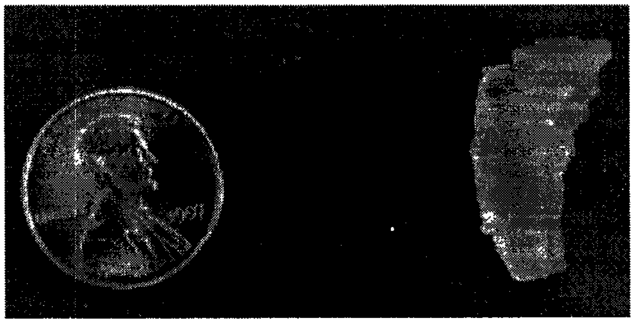
Figure 4-5 Final Edited Scanning Polylines of the First Reconstruction Trial.

To prepare a "build", the .stl file of each fragment is loaded into Maestro. Maestro is used to correct errors and convert the .stl file created by DataSculpt. The supports for each part are generated and the parameters of the supports can be edited in Maestro. When both the supports and part are ready, it is sliced and Maestro creates the four necessary files for the building process in the SLA-250.

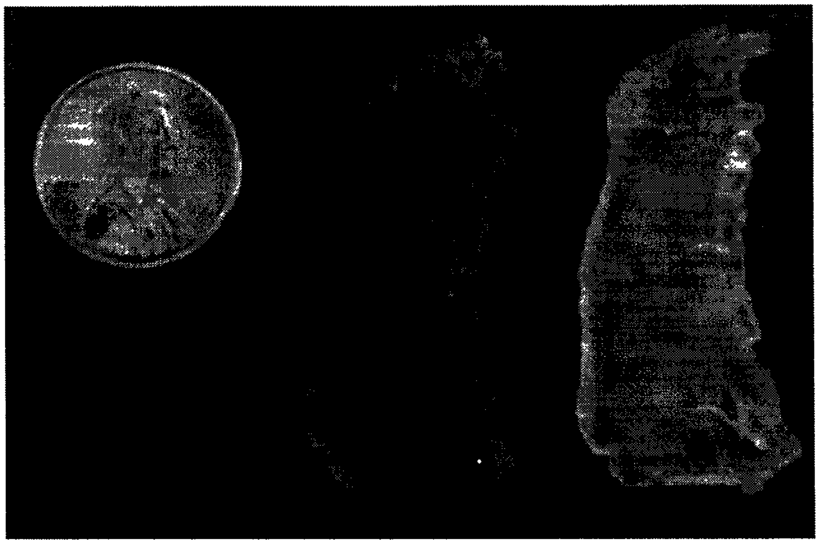
4.2.3 The Final Product

To start building in the SLA-250, the four files have to be loaded into the controller of the SLA-250. The controller provides a graphic simulation of the building process, options to check the power of laser beam and the temperature of the resin. The total time needed for building parts and supports mainly depends on the total volume of the object.

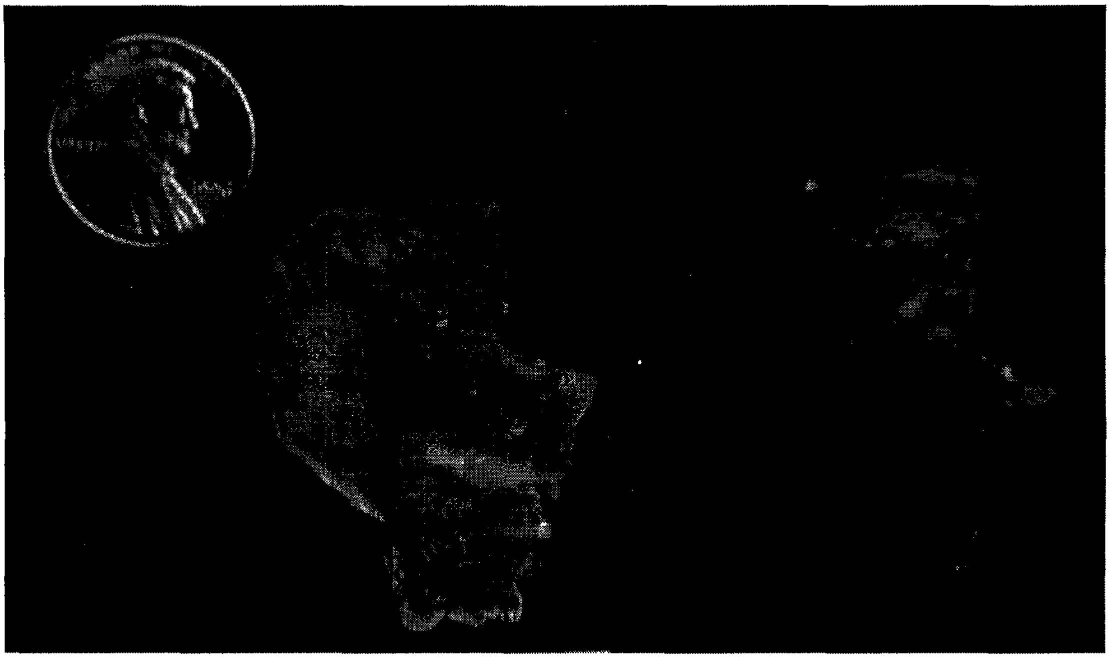
The right jaw, left jaw, and facial skull were reconstructed in the first reconstruction trial. Figure 4-6 shows pictures of both the SLA duplicate and the epoxy duplicate of the three fossil fragments. From the pictures, it appears some important features of the fossils are lost in the first reconstruction trial. Note that the teeth of both broken jaws are straight down to the gum line and the bone's concave areas are flattened. These errors mainly result from the scanning procedures because only rotational scanning was implemented in the first reconstruction trial.



(a) Left jaw. Left, scanned epoxy duplicate. Right, SLA duplicate of the first reconstruction trial.



(b) Right Jaw. Left, scanned epoxy duplicate. Right, SLA duplicate of the first reconstruction trail.



(c) Facial Skull. Left, SLA duplicate of the first reconstruction trial. Right, scanned epoxy duplicate.

Figure 4-6 Scanned Specimens and the SLA Duplicates of the First Reconstruction Trial.

4.3 The Second Reconstruction Trial

The second reconstruction trial for the same *Homunculus* fossils aimed to improve the quality of the part geometry. Because of the scanning design and the complex shape of the fossils, lots of concave surfaces are not preserved in the SLA duplicates built during the first trial. Combined scanning, which is composed of multiple flat scanning and rotational scanning, was applied to collect more surface information for the second reconstruction.

4.3.1 Fossil Scanning

In order to collect more surface data, combined scanning is employed this time. Each specimen was attached on the shaft as in the first trial, and the orientation of attachment for each specimen was also the same. To compare the products based on the same specimen developed in two different reconstructions, the line density in both the rotational scanning and flat scanning were identical to the line density in the rotational scanning of the previous trial. The other preparation steps for combined scanning included coating with baby powder and a paper box put under the specimen.

For each part, rotational scanning was performed first, then followed by multiple flat scanning with the object kept in the same position. After the rotational scanning was finished, the original scanning data was loaded into DataSculpt for examination to decide the various angles needed for the multiple flat scanning passes. The size of the scanning area for each flat scanning window depending on the size of the critical area may be different. Different specimens need different angles for the multiple flat scanning windows to supply missing data, because they have totally different geometries. For example, the right jaw required only two more flat scanning runs to supplement the rotational scanning, but the facial skull needed nine flat scanning windows to avoid loss of surface data. The line density of all flat scanning windows must be exactly the same as the rotational scanning. This assures that all scanning polylines which have the same x coordinates fit together. Table 4-4 lists the scanning densities, number of flat scanning windows and the rotation angles for multiple flat scanning of each specimen. Table 4-5 lists the scanning time of rotational and flat scanning used and the number of points of both two scanning collected in the second reconstruction trial.

	Line Density of both Rotational and Flat Scanning	Point Density of Rotational Scanning	Point Density of Flat Scanning	Number of Flat Scanning Windows	Rotation Angles for Each Flat Scanning Window
Left Jaw	.25mm	1°	.25mm	3	45°,250°, 325°
Right Jaw	.25mm	1°	.25mm	2	90°,270°
Facial Skull	.25mm	1°	.25mm	9	0°, 30°, 60°, 85°, 180°x2, 270°, 315°, 345°
Top Face	.25mm	1°	.25mm	5	45°, 90°, 225°, 270°, 315°
Bottom Face	.25mm	1°	.25mm	6	0°, 45°, 90°,135°, 180°, 300°

Table 4-4 The Scanning Density and the Rotation Angles for Flat Scanning Used in the Second Reconstruction Trial.

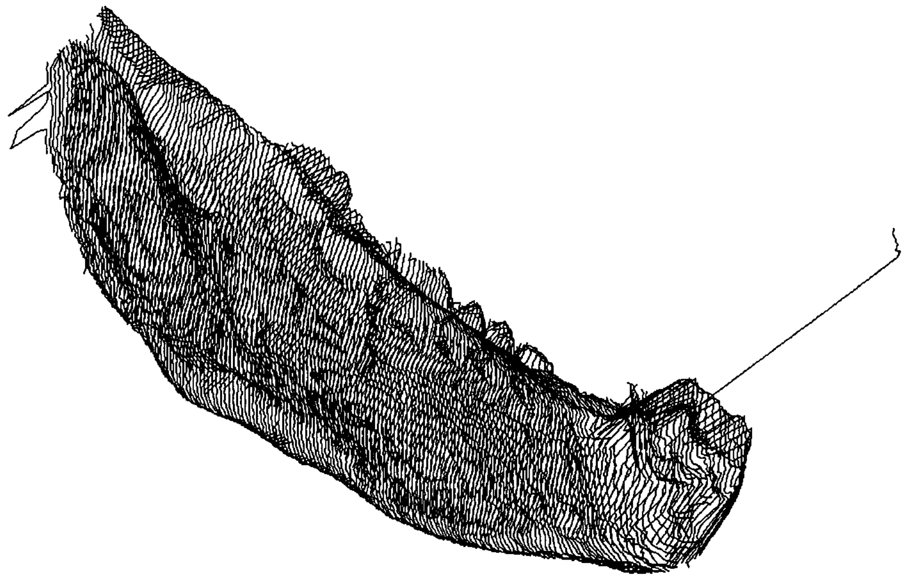
	Points Collected of Rotational Scanning	Points Collected of Flat Scanning	Total Points Collected in This Trial	Scanning Time of Rotational Scanning	Scanning Time of Multiple Flat Scanning	Total Scanning Time Used
Left Jaw	33,568	7,457	41,025	2:15:50	0:28:32	2:41:22
Right Jaw	63,896	19,393	83,289	3:23:27	1:14:11	4:37:38
Facial Skull	60,648	53,750	114,398	4:56:19	3:28:18	8:24:37
Top Face	44,400	26,487	70,887	5:38:06	3:13:35	8:51:41
Bottom Face	44,317	51,275	95,592	4:52:39	9:08:49	14:01:28

Table 4-5 The Scanning Time Used and Number of Points Collected in the Second Reconstruction Trial.

4.3.2 Data Editing

After both rotational and flat scanning is completed, all the scanning data from different scanning windows are loaded into DataSculpt. Each "layer" representing a different flat scanning window has to be rotated to the original coordinate system that is used to scan the specimen in the window. Figure 4-7 shows multiple flat scanning layers of the right jaw in an isometric view; respectively, (a) is before rotation and (b) is after rotation. In most cases, because the same information was collected the scanning polylines from different layers may partly overlap each other.

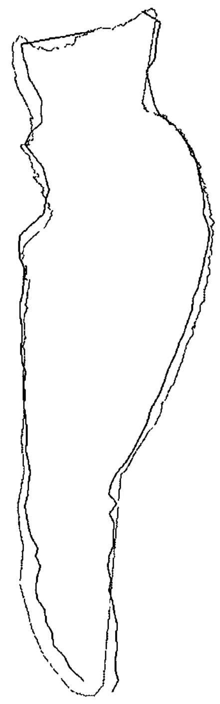
(a) Before rotation (Actual size: L:44.56mm, H:22.85mm; Rotation Angle: 90°, 270°).



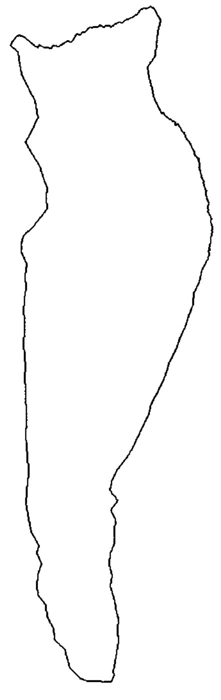
(b) After rotation (Actual size: L:44.56mm, W:8.40mm, H:22.85mm).

Figure 4-7 Scanning Polylines of the Right Jaw Before and After Rotation.

It is time consuming work to edit the scanning information composed of rotational scanning and several layers of flat scanning. For each cross-section of scanning polylines, the drop-off or spike segments must be replaced by another polyline segment which reflects the original shape. The errors must be deleted first then merged or blended with other detailed scanning polylines. Polylines may have overlaps formed by two or more different layers at any part of the polyline. If there are two or more similar scanning polylines for the same part of a cross-section, the editor can either leave one and delete the others or blend both of them into one polyline. The direction of the point sequence forming each polyline also has to be the same, for converting the .scn file into a .msh file. Figure 4-8 is one cross-section made up of three scanning polylines of the right jaw; respectively, (a) is before editing and (b) is after editing.



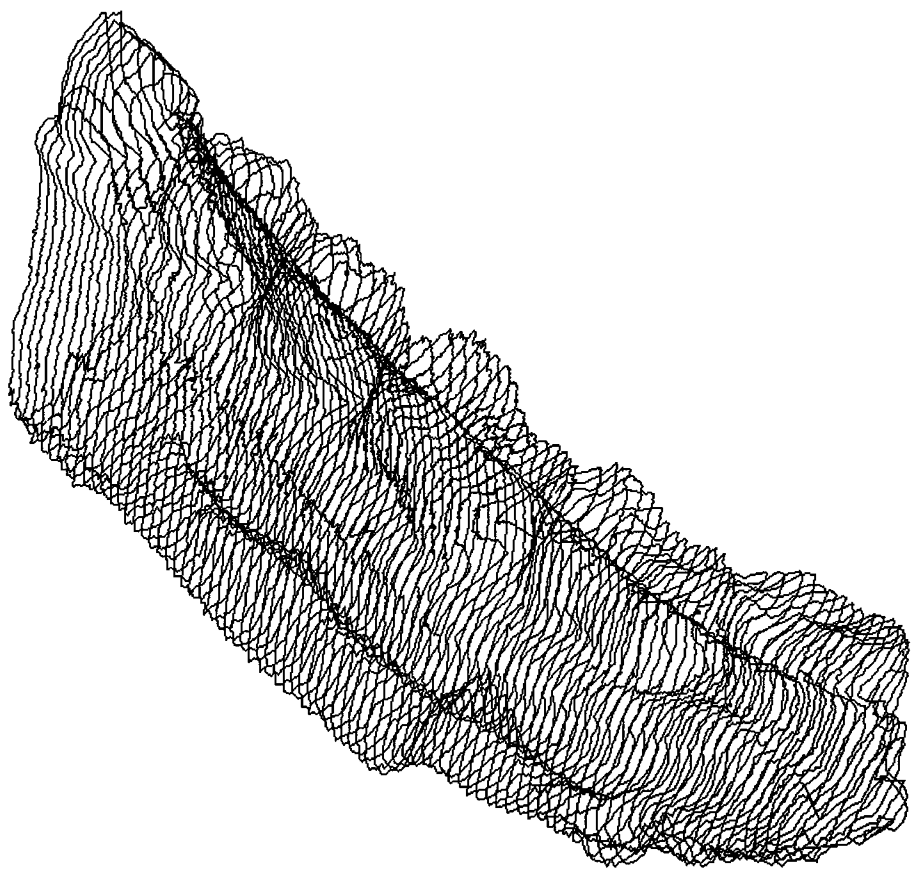
(a) Before editing (Actual size: W:4.57mm, H:16.15mm).



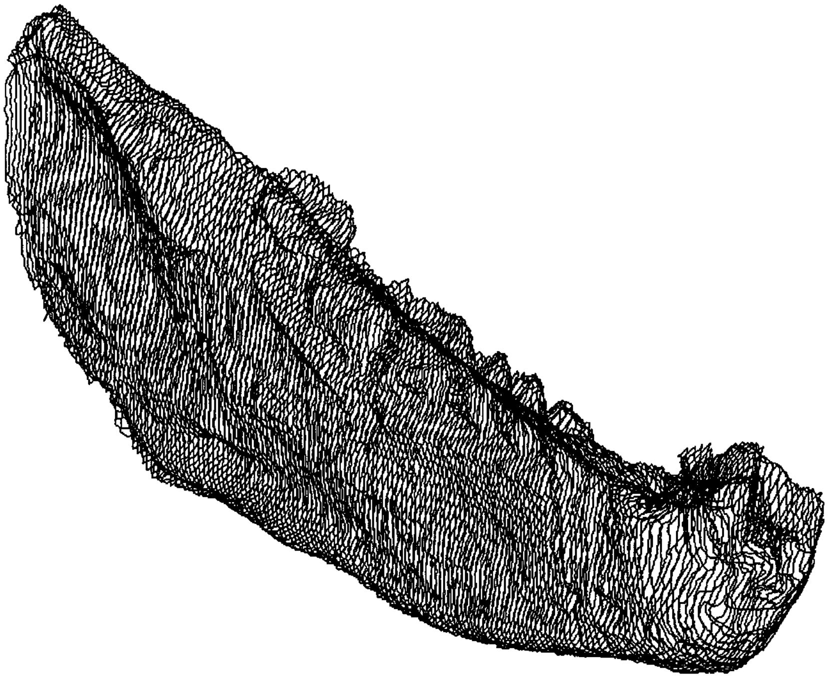
(b) After editing (Actual Size: W:4.57mm, H:16.15mm).

Figure 4-8 A Scanning Polyline of the Right Jaw.

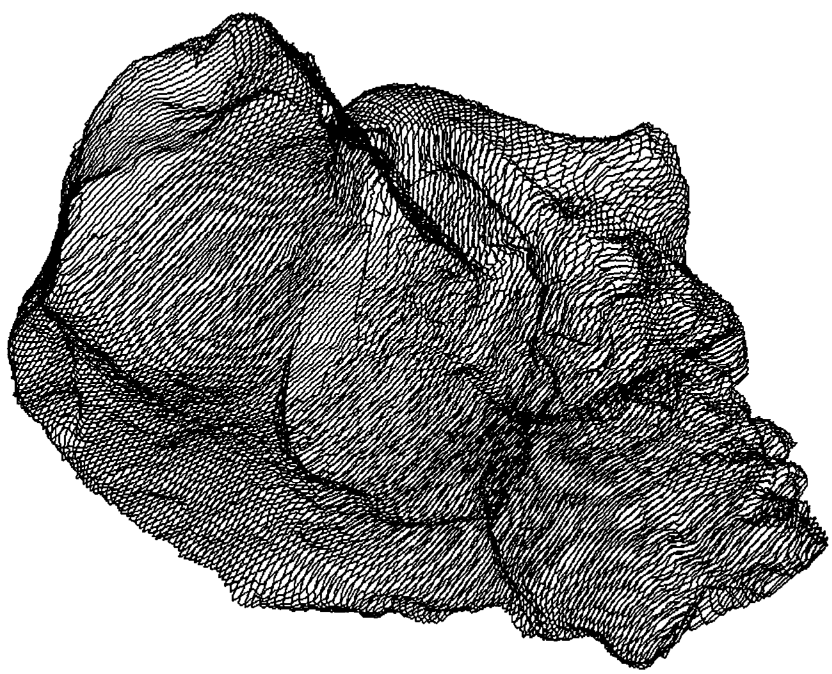
The final complete, edited scanning data is converted into mesh file format (.msh file) after all data of different layers has been edited into one layer, as in Figure 4-9. For each object, the whole fi0nal edited scanning data is converted into a .msh file which is converted into a .stl file. Like the first reconstruction process, all the .stl files are processed by using Maestro then transferred to the SLA-250 for building duplicates.



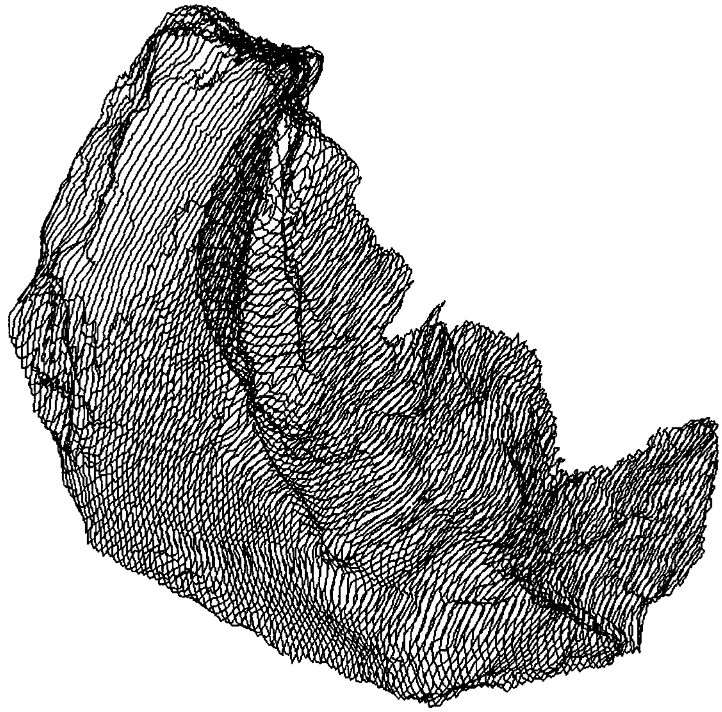
(a) Left jaw (Actual size: L:23.88mm, W:5.97mm, H:13.69mm).



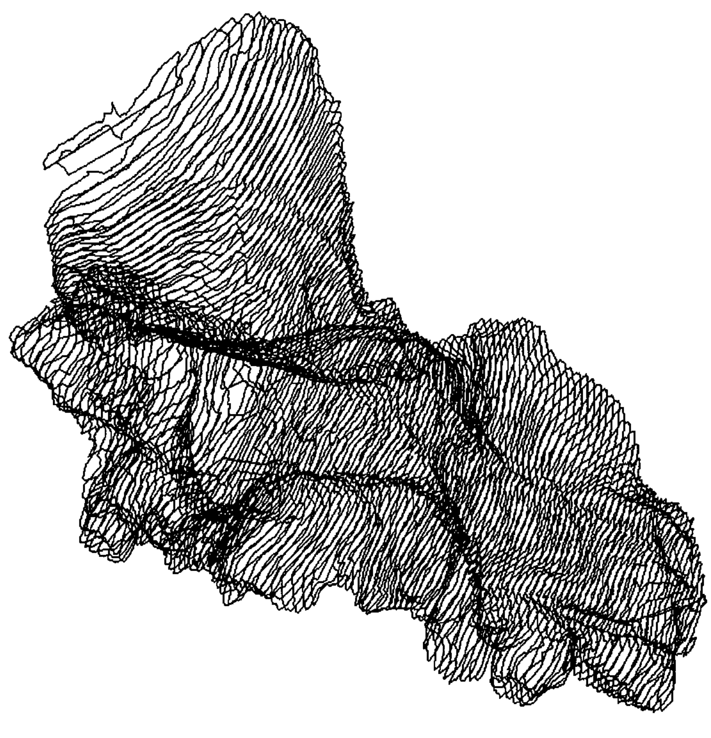
(b) Right jaw (Actual size: L:44.56mm, W:8.40mm, H:22.85mm).



(c) Facial skull (Actual size: L:41.37mm, W:29.42mm, H:17.23mm).



(d) Top face (Actual size: L:28.08mm, W:16.76mm, H:21.13mm).



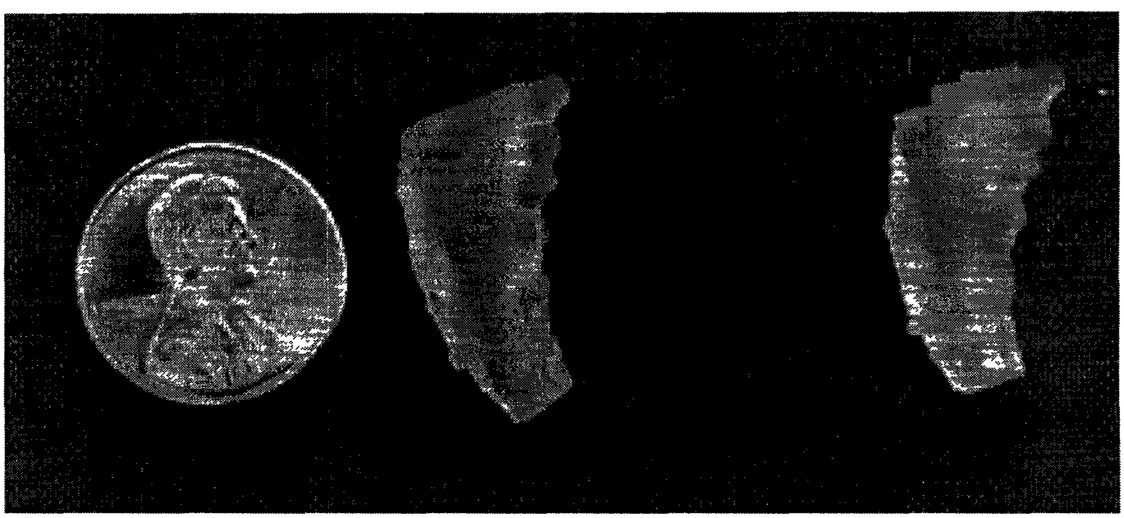
(e) Bottom face (Actual size: L:29.85mm, W:16.80mm, H:20.22mm).

Figure 4-9 Final Edited Scanning Polylines of the Second Reconstruction Trial.

4.3.3 Final Product

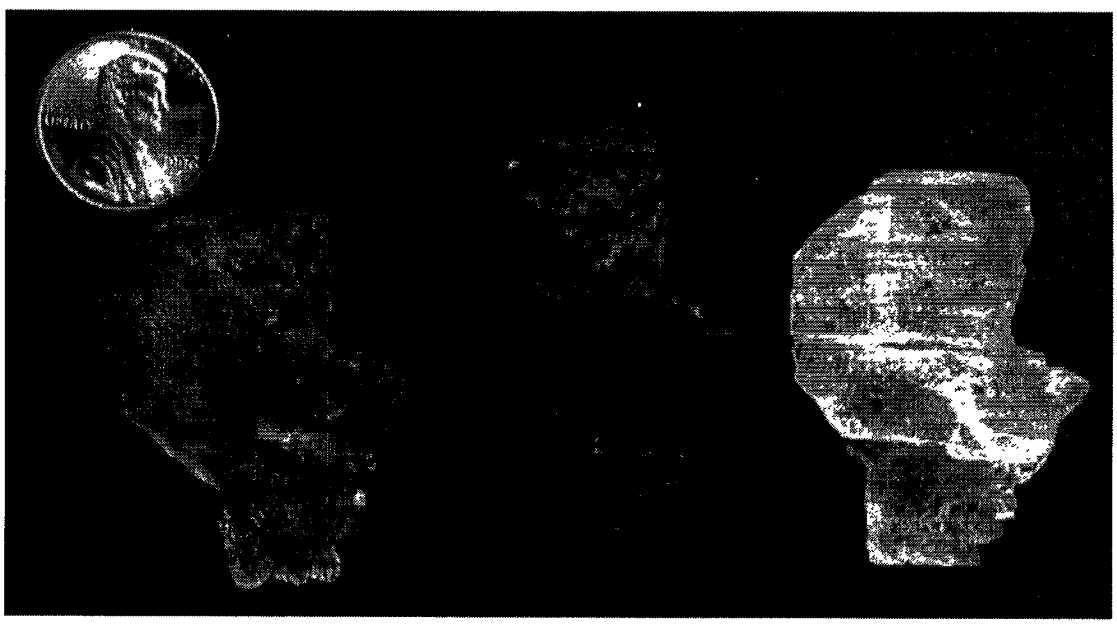
The SLA products of this reconstruction practice using combined scanning improve those of the last reconstruction using only rotational scanning. The different angles of multiple flat scanning can make up for the loss of data in rotational scanning. Compared with the original specimen, concave surfaces have been captured in the second reconstruction process, and detailed features of teeth are also improved by this method.

In the second reconstruction practice, all of the five fossil fragments were reconstructed by using the SLA-250. Figures 4-10 are the SLA products of the first and second reconstruction trials and the original fossil fragments. By inspecting the SLA duplicates closely, one find some small cracks and redundant flanges which are not evident in the fossil. The third reconstruction aims to correct the errors by using the same scanning data from the second reconstruction trial.

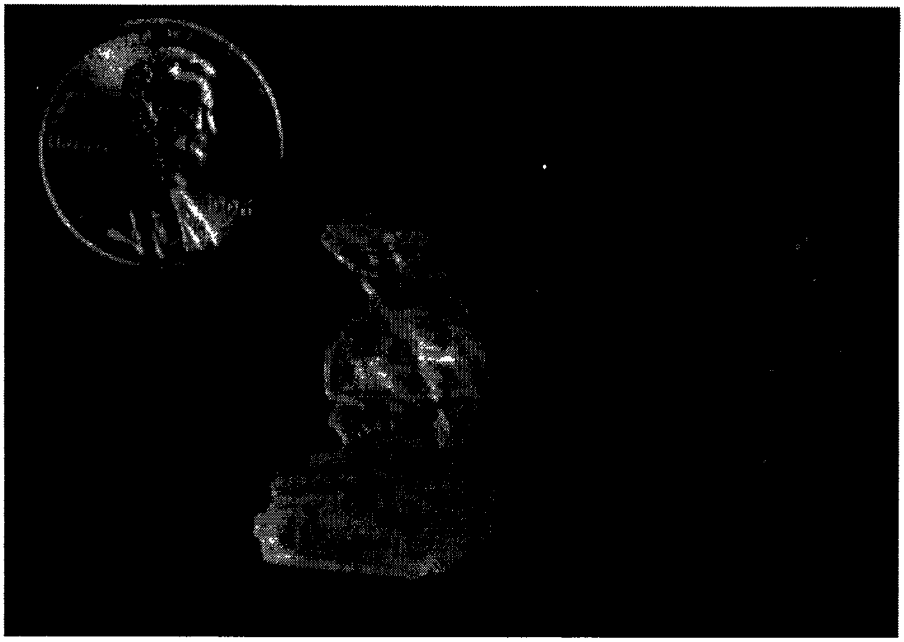


(a) Left jaw. Left, SLA duplicate of the second reconstruction trial. Center, scanned epoxy duplicate. Right, SLA duplicate of the first reconstruction trial.

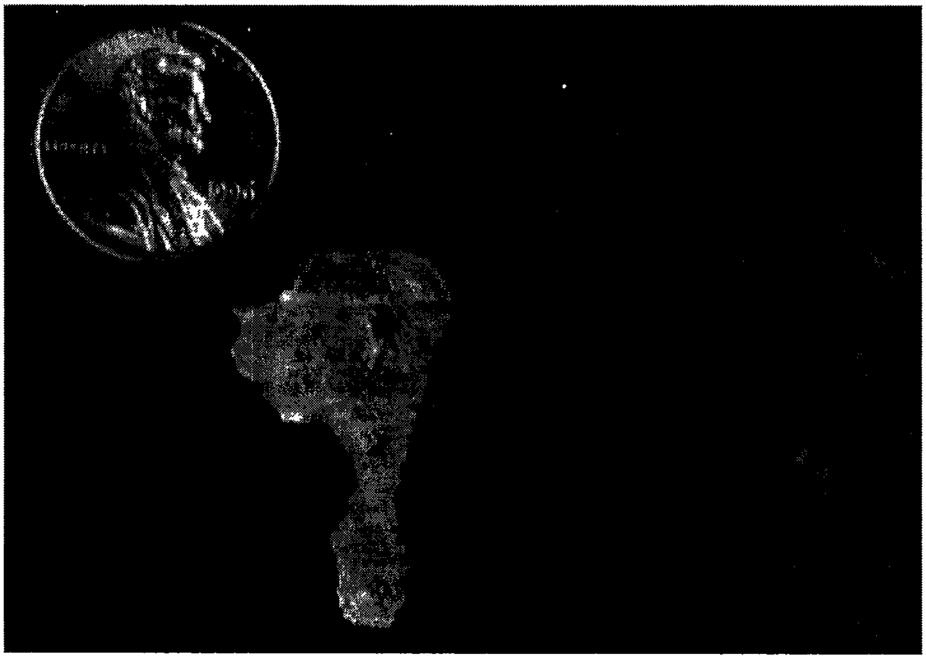
(b) Right jaw. Left, SLA duplicate of the first reconstruction trial. Center, scanned epoxy duplicate. Right, SLA duplicate of the second reconstruction trial.



(c) Facial skull. Left, SLA duplicate of the first reconstruction trial. Center, scanned epoxy duplicate. Right, SLA duplicate of the second reconstruction trial.



(d) Top face. Left, SLA duplicate of the second reconstruction trial. Right, Scanned epoxy duplicate.



(e) Bottom face. Left, SLA duplicate of the first reconstruction trial. Right, scanned epoxy duplicate.

Figure 4-10 Scanned Specimens and the SLA Duplicates of the First and Second Reconstruction Trials.

4.4 The Third Reconstruction Trial

The third reconstruction tries to fix the cracks and delete the redundant flanges to produce a better replica. The third reconstruction practice utilizes the final edited scanning data of the second reconstruction practice for each specimen to create .stl files for building in the SLA-250. The edited scanning data of the second practice for each specimen, however, is converted by a different technique into mesh files for the third practice.

4.4.1 Data Processing

All the data used in this trial was completely edited in the last trial, and the final edited scanning files were proven to accurately represent features of the fossils, so no additional fossil scanning was necessary. To delete artificial cracks and flanges, a different triangulation algorithm was employed. However, some of the error triangles could not be fixed. DataSculpt has three formats of triangulation, which are local, global and diagonal, and the default triangulation is local. A scanning file and the output mesh file can be viewed by rendering the object, and the default of shading is local triangulation as well. The mesh file using diagonal triangulation can not be shaded, so only local and global triangulation are used in the third trial.

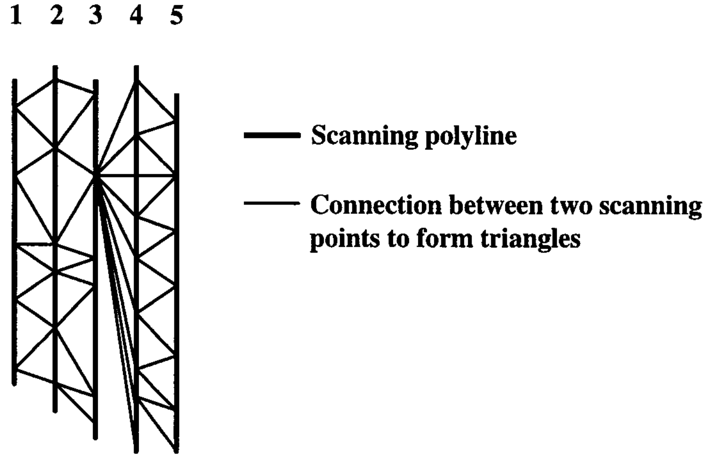
When a final edited scanning file is ready to export as a mesh file, it can be observed by using the shade routine. If it miraculously looks perfect, the scanning file could be stored as a mesh file directly. Usually this is not the case. For example, rendering all scanning file of the five fossil fragments produce some cracks and flanges in either local and global shading. Actually, these error triangles can not be fixed by Maestro. They appear to be produced by DataSculpt. Because the same edited files used for the second practice are all analyzed and overwritten by Maestro, however, the final SLA products still have cracks and flanges.

Changing the triangulation algorithm in DataSculpt is a feasible way to correct individual errors, but it also requires multiple mesh files. In this trial, all the final scanning files of the fossil fragments were re-examined by using the local shading first, and the scanning polylines of each file need to be sorted by X-axis in advance. It is necessary to inspect the shading image of a final scanning file from different points of view to find out the location of errors. In most cases, the cracks and flanges are between two scanning polylines that have been mistakenly connected by the triangulation algorithm of DataSculpt (Figure 4-11(a)). After locating the regions where the errors are created, the whole scanning file is separated into several sections.

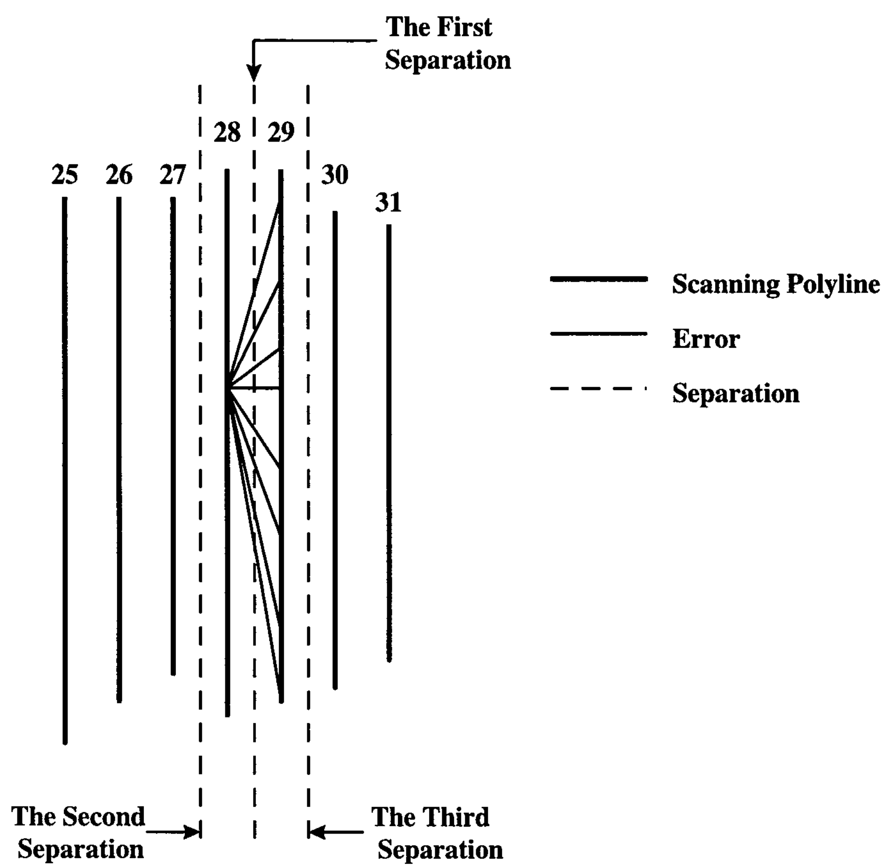
Three separations are required to repair one error, which lies between two adjacent cross-sections, or scanning polylines. Using a front or top view is recommended in separating a scanning file in DataSculpt. Because the scanning file has been sorted along the X-axis, the scanning polylines are numbered from left to right. Before starting separations, the rendering process uses the local shading default first, then starts rendering from left to right, according to the number sequence of polylines. The sequence of all cross-sections of a scanning file must be maintained in the separation work, although the file is divided for changing the triangulation mesh. For consistency, the work of changing triangulation starts from the left end of the scanning file proceeds to the other end.

Figure 4-11(b) provides an illustration of the method. Assuming the first error occurs between the twenty eighth and the twenty ninth polylines of a scanning file. The first separation divides the two polylines (28 and 29) that have been incorrectly meshed by the algorithm so it can be re-meshed later. The second separation isolates one of these (28) from its neighbors (polylines 1....26,27). The third separation isolates its partner (29) on the opposite side of the error from its neighbor (polylines 30,31....). Three new temporary sections are created: (1) polylines [1-28]; (2) polylines [28-29]; (3) polylines [29, 30....]. The first section (polylines 1-28) is meshed using the local algorithm without change. Then, the second section, containing the error triangles, is re-meshed by the alternative algorithm, global. If the error is still there, the triangulation which creates the least error is chosen. In most cases, the cracks and flanges are fixed or reduced after changing the triangulation routine. The preceding steps are repeated to fix the next error until all of the errors of the scanning file are repaired. This results in a single scanning file having a continuous even mesh.

The next step is to convert all separated small mesh files (.msh) into .stl files, then the .stl files are loaded into Maestro for processing. Since the three separations split the error and the left correct section precisely, there is no collapse between any two adjacent .stl files. After loading the separated .stl files, all of them can be combined into a single .stl file simply using the command "combine". Like the processes in the last two practices, the new combined .stl file will be analyzed then sliced to generate the four files needed for the building process in the SLA-250.



(a) An error occurs between scanning polyline 3 and 4.

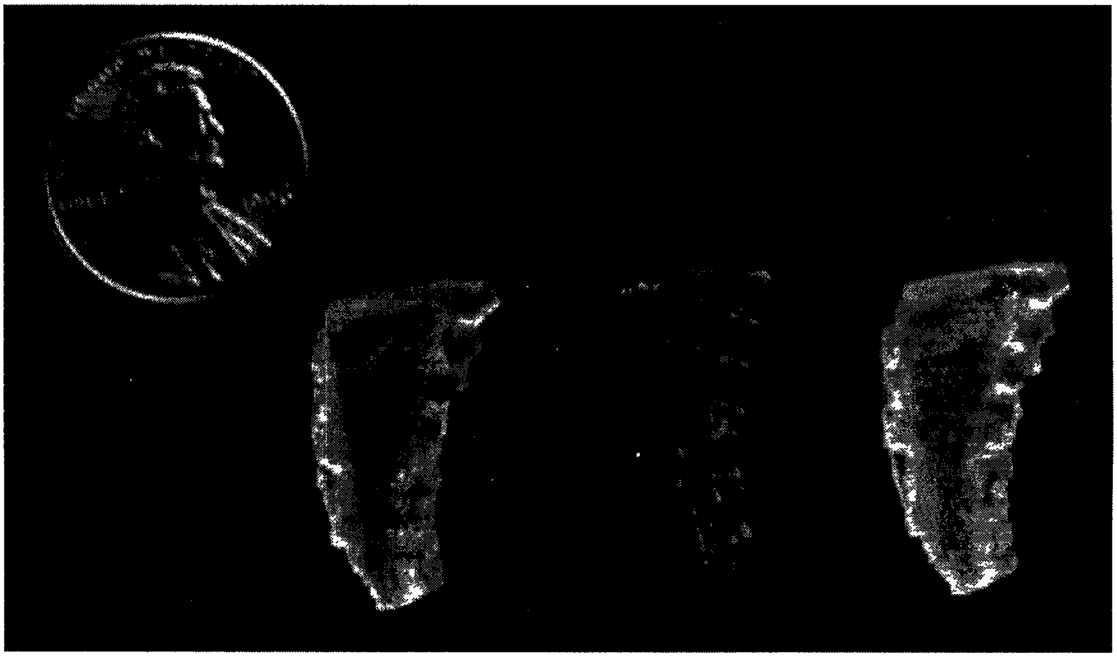


(b) The three separations for an error.

Figure 4-11 The Separation Method Used in the Third Reconstruction Trial.

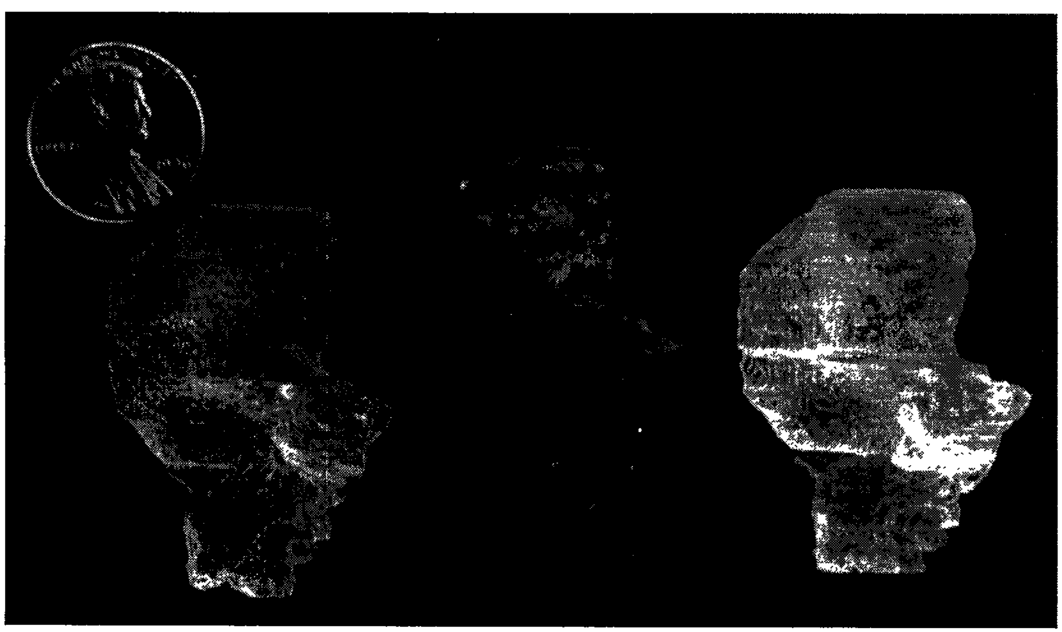
4.4.2 Final Product

The SLA duplicates of this practice are better than those of the second attempt. Not only are the concave surfaces presented, but the cracks and flanges are also reduced. Many have even disappeared. The pictures in Figure 4-12 are the SLA duplicates of the second and third trials and the fossil fragments used in this case study. The best improvement is for the right jaw of *Homunculus* (Figure 4-12(b)). The SLA duplicate of the right jaw is broken in the second trial, because the one of its cracks is too serious to create any connection. The big crack, however, is fixed by changing its triangulation in the third practice.

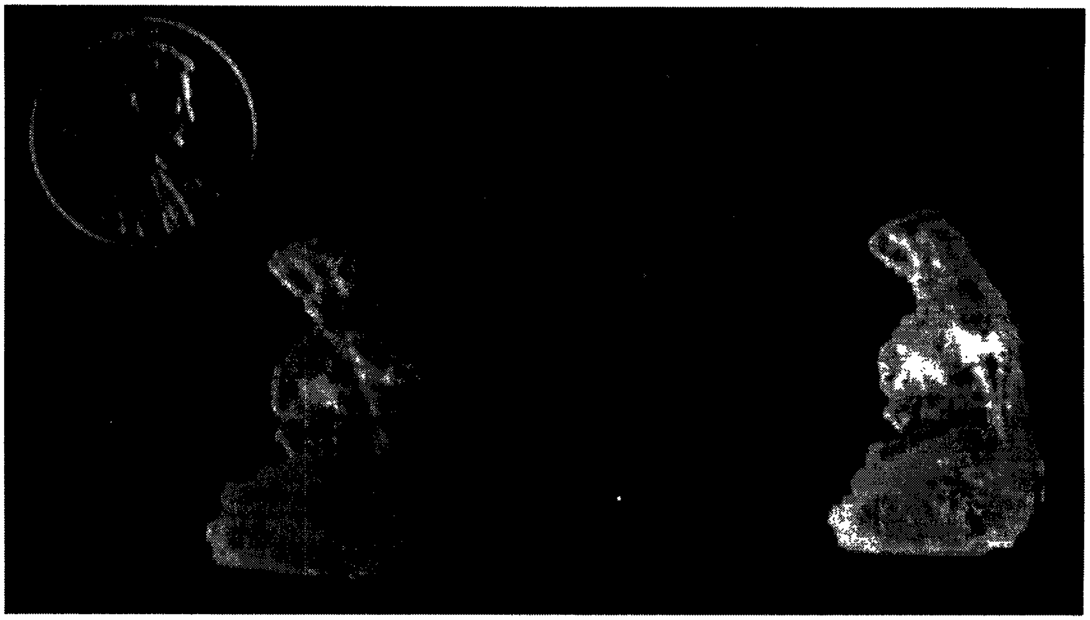


(a) Left jaw. Left, SLA duplicate of the second reconstruction trial. Center, scanned epoxy duplicate. Right, SLA duplicate of the third reconstruction trial.

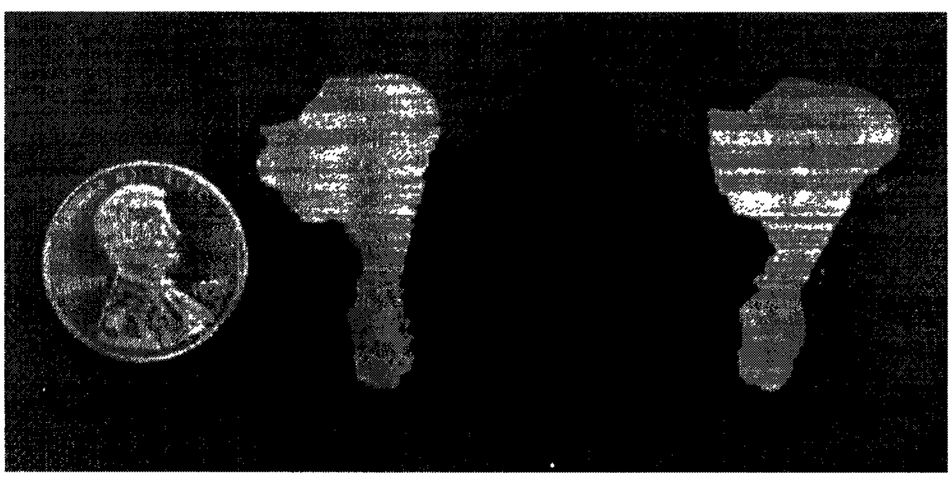
(b) Right jaw. Left, SLA duplicate of the third reconstruction trial. Center, scanned epoxy duplicate. Right, SLA duplicate of the second reconstruction trial.



(c) Facial skull. Left, SLA duplicate of the third reconstruction trial. Center, scanned epoxy duplicate. Right, SLA duplicate of the second reconstruction trial.



(d) Top face. Left, SLA duplicate of the second reconstruction trial. Center, scanned epoxy duplicate. Right, SLA duplicate of the third reconstruction trial.



(e) Bottom face. Left, SLA duplicate of the second reconstruction trial. Center, scanned epoxy duplicate. Right, SLA duplicate of the third reconstruction trial.

Figure 4-12 Scanned Specimens and the SLA Duplicates of the Second and Third Reconstruction Trials.

All of the five fossil fragments are utilized for reconstruction using the SLA-250 in this trial. The SLA products of the third practice are the final products for the fossil fragments in this case study. The reproduction of more SLA duplicates for each fossil uses the combined .stl file of the fossil in the third trial to manufacture.

4.5 Skull Reconstruction

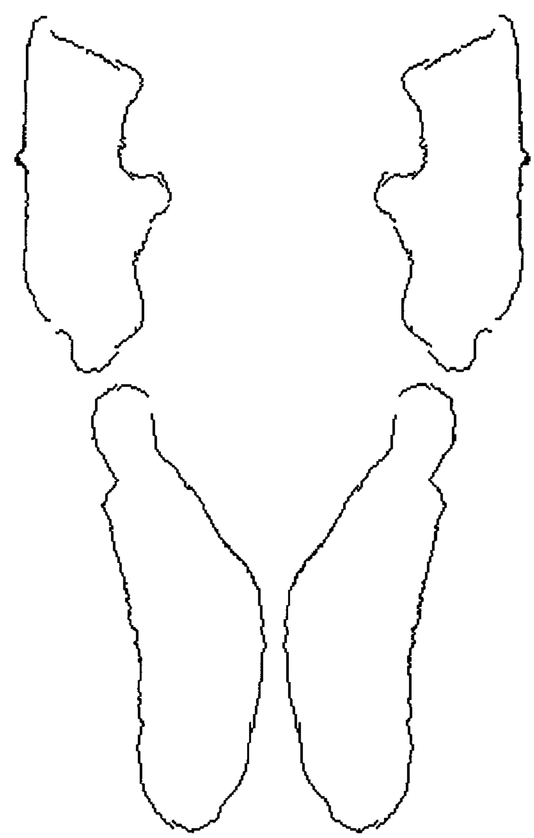
A whole skull of *Homunculus* needs to be reconstructed by using the final edited scanning file of the second trial. The three edited scanning files of right jaw, top face and bottom face were used as the basis for a full reconstruction in a CAD environment. The three files were moved, rotated and mirrored in DataSculpt to form a whole skull with the guidance of Dr. Rosenberger. The whole skull was also built in the SLA-250 to provide a physical model for finalizing the details of the digital reconstruction.

4.5.1 Data Processing

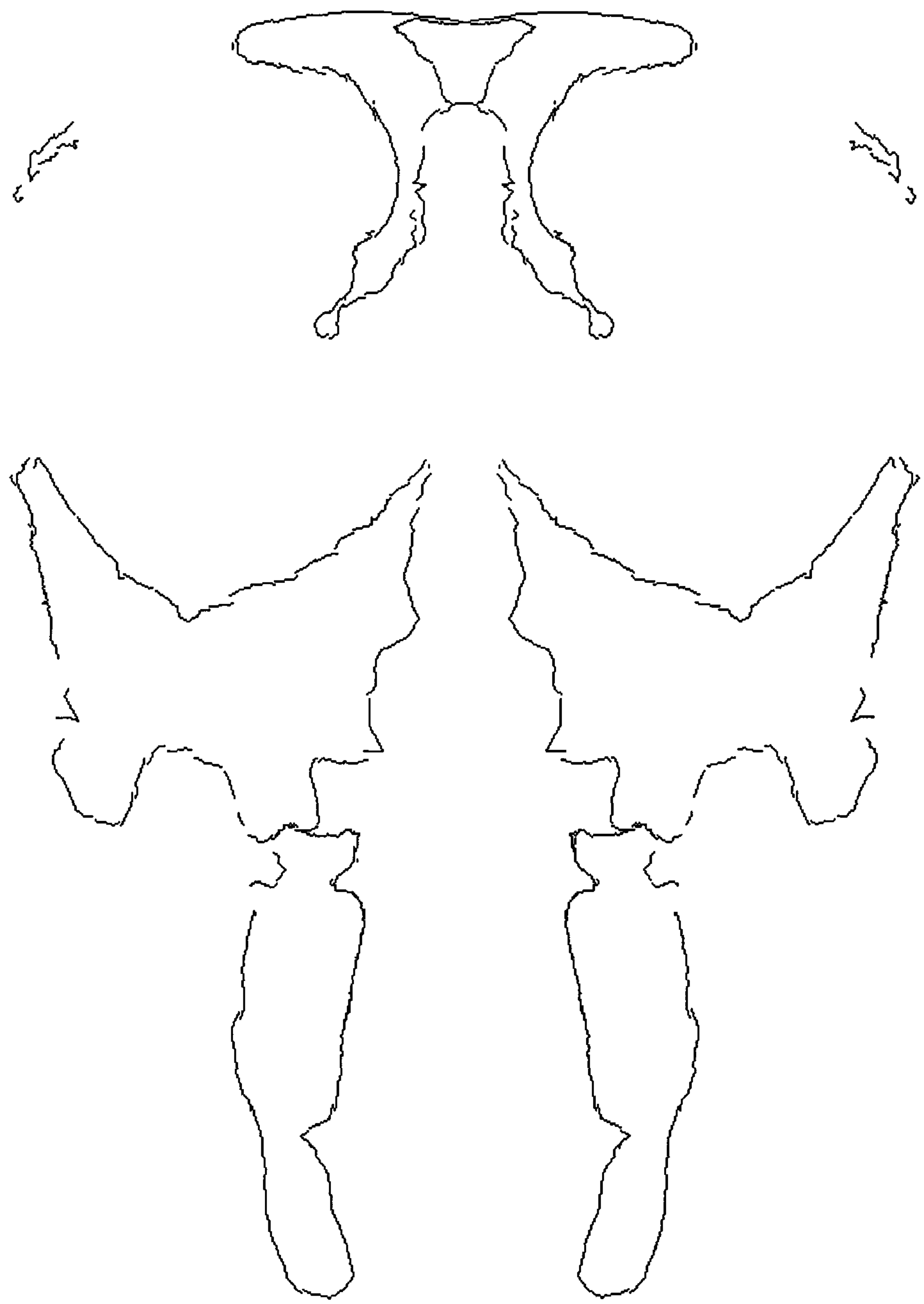
The three final edited scanning files of right jaw, top face and bottom face were employed to reconstruct the model of *Homunculus* in DataSculpt. All of the three edited scanning files had been used to build SLA duplicates in the second and third reconstruction trials. The right jaw fragment, which is more complete than the left, was mirrored to form a full bottom jaw, based on a natural anatomical center line for the mirror-image projecting through the front-most point of the right jaw. The axis of rotation was set vertical to the center line and parallel to Z-axis. After rotation, the right jaw was mirrored about the center line to form a continuous lower jaw.

The top portion of the face, which preserved the anatomical midline, was set aside until the bottom of the face could be aligned with the teeth of the lower jaw. It was provisionally placed in alignment with the centerline of the jaw based on their natural midlines, which go through the bridge of the nose between the eye sockets.

The bottom face was positioned according to the match of its teeth and the teeth preserved in the jaw. The last tooth of bottom face fragment naturally meets right above the last tooth of the jaw, so it can be used as a reference point. The first two teeth of bottom face, including the large canine tooth, were also used to match the counterparts of the lower jaw. The pictures of Figure 4-13 are the scanning polylines of the cross-section showing where the teeth of the bottom face and the lower jaw are aligned; (a) is for the first tooth and (b) is for the last tooth.



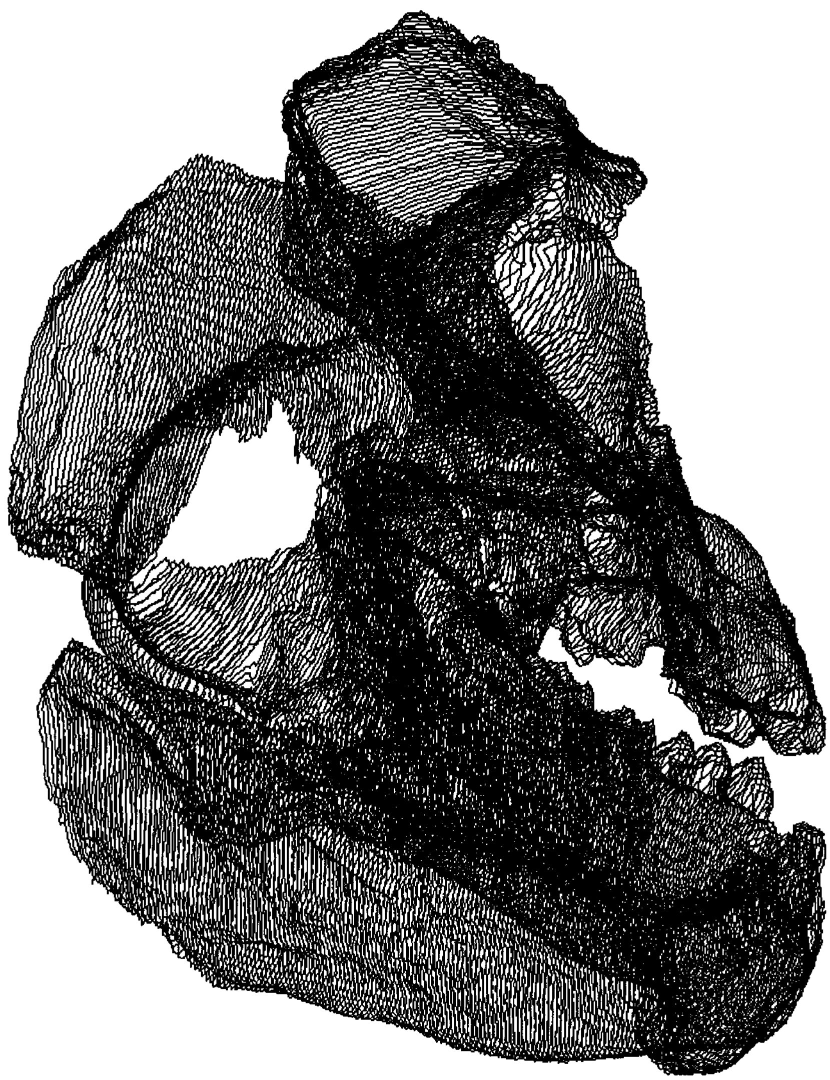
(a) The first tooth (Actual size: W: 16.92mm, H:26.44mm).



(b) The last tooth (Actual size: W:33.83mm, H:44.81mm).

Figure 4-13 Two Cross-Sections of Whole Skull.

The eye socket, which is well preserved on the inside-back surface was used to locate the top face and bottom face. In the digital reconstruction there was little overlap between these parts of the orbit, so the two specimens could be joined together accurately. After organizing the facial skull with these parts, the composite was mirrored to make a right side and a complete face. The center line was through the middle of the nasal and frontal bones of the top face for the mirror image. Figure 4-14 shows the whole scanning polylines of a complete skull; respectively, (a) from an isometric view, (b) from a right view. The .stl files of the whole skull were then created by using the separation method of the third reconstruction trial.



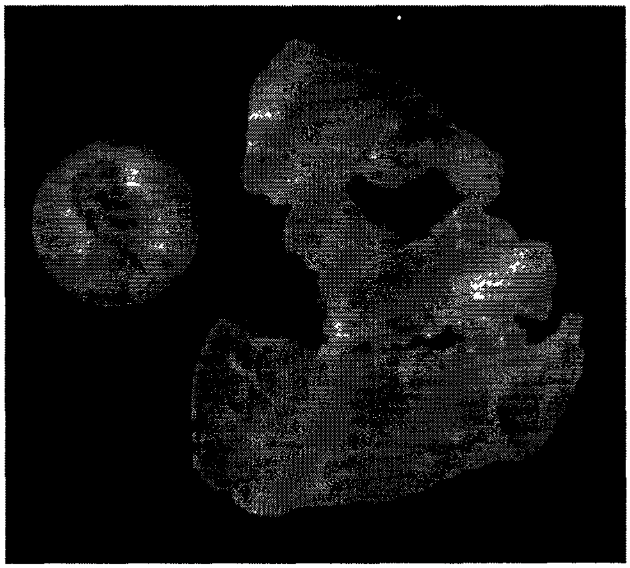
(a) From an isometric view (Actual size: L:41.43mm, H:47.40mm, W:36.32mm).

(b) From a right view (Actual size: L:41.43mm, H:47.40mm, W:36.32mm).

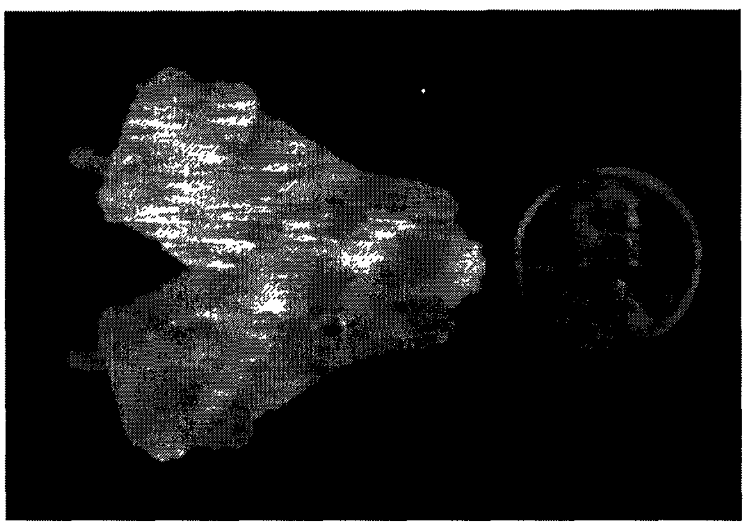
Figure 4-14 The Final Whole Scanning Polylines of *Homunculus* Skull.

4.5.2 Final Product

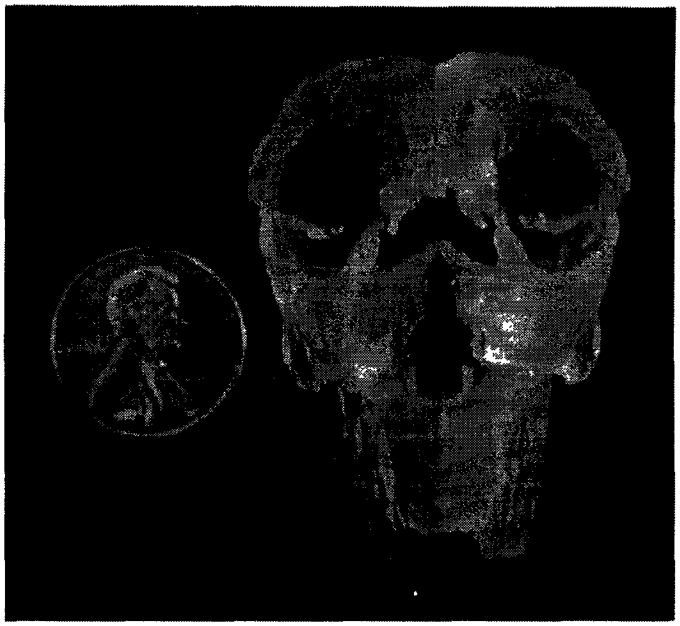
All the separate .stl files of the skull were loaded into Maestro and then combined into six .stl files for the analysis. The six .stl files of the whole skull included files of the three original skull parts, right jaw, top face, bottom face and their mirror images. All three images were mirrored along the center line to complete a whole skull. The six .stl files were analyzed and fixed using Maestro and then combined into a single .stl file of the skull. After combination, supports were created by Maestro. Then the four building files were prepared and loaded into the controller of the SLA-250 for building process. The pictures of Figure 4-15 are the final SLA duplicate of the skull in different views.



(a) Front view.



(b) Top view.



(c) Right view.

Figure 4-15 The Final Whole SLA Duplicate of *Homunculus* Skull.

Chapter 5

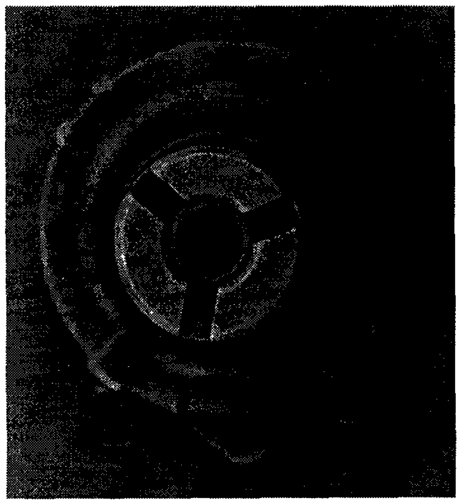
Case Study II: Object Reconstruction of a Distributor

5.1 Introduction

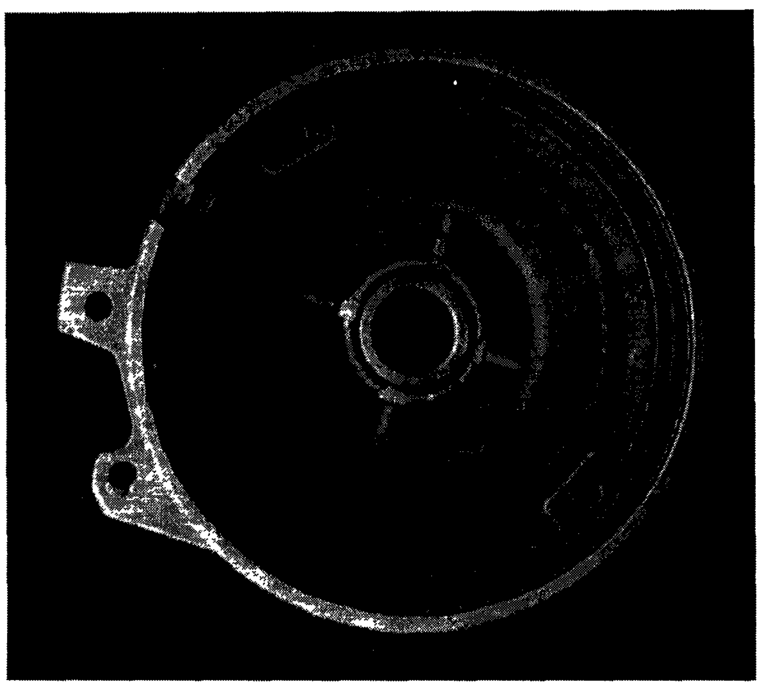
In this chapter, Case Study II, a distributor housing of a Ford pick-up truck of the 1970s is used as the model for object reconstruction. Figure 5-1 shows the distributor housing from different points of view. This reconstruction tries to create a new system design for reverse engineering. Laser scanning can replace the manual measurements and the different CAD software packages may combine different files into a single file. By using these advanced technologies, a part or tool may be reconstructed without its blueprints and then mass produced for industry.

The distributor is an important part used for ignition of the engine, because it distributes high-voltage currents regularly to the spark plugs. The spark plugs ignite the mixture of gas and air to explode, and the explosions provide the power needed to move the pistons up and down. Of course, the movement of pistons is the motive source of a running engine. For brevity, the distributor housing is called as distributor in this chapter.

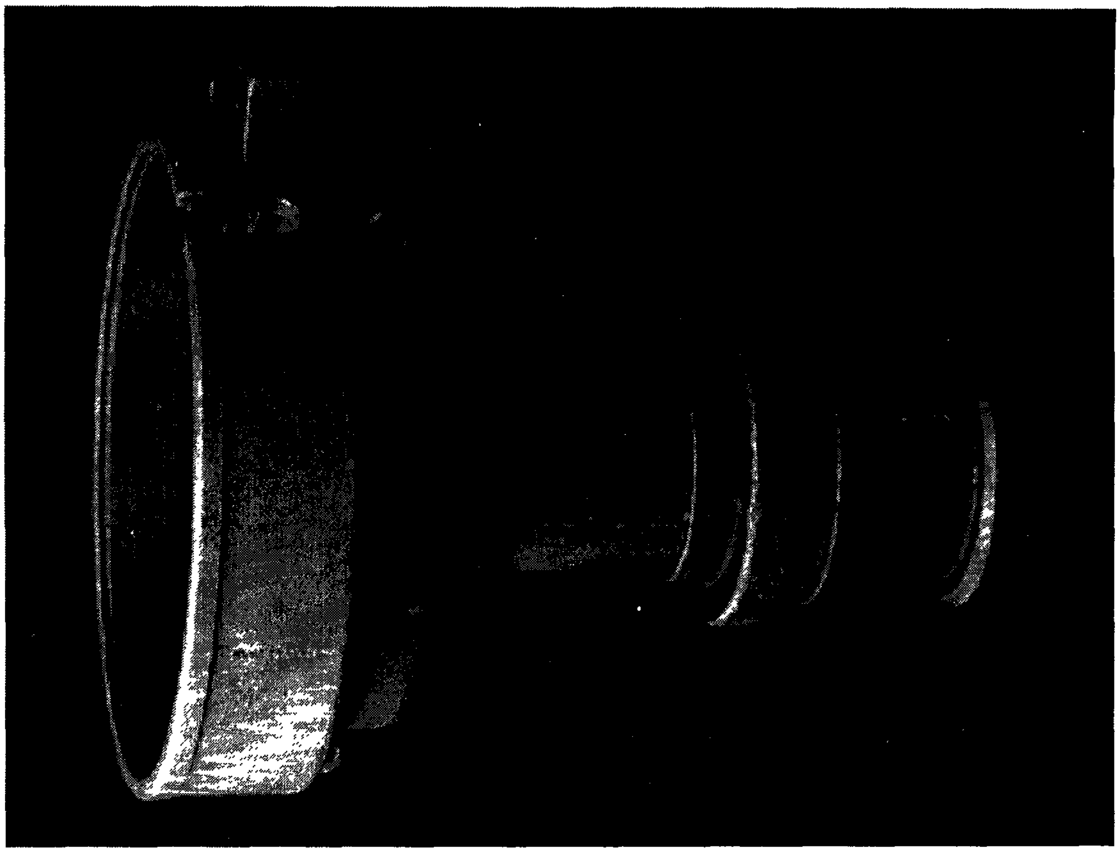
In this project, reconstruction of the distributor is a new challenge for rapid prototyping, because the manufacturing process begins without using blueprints. Instead, the three dimensional laser scanner is used to measure its surface in place of blueprints. The distributor has some important interior features that require reconstruction. However, the end features are hard to scan when the distributor is mounted along the A-axis. It is thus necessary to combine different files which are not scanned within the same coordinate framework, which introduces new challenges in data developments.



(a) Top view.



(b) Bottom view.



(c) **Side view.**

Figure 5-1 Pictures of the Distributor from Top, Bottom and Side Views.

5.2 Distributor Scanning

The distributor is symmetric shape and has some important interior features, which include a hollow cylinder for a shaft through the distributor. Since it has a symmetric shape, the rotational scanning is an ideal approach for the exterior. However, scanning the interior requires two flat scanning windows at the top and bottom ends of the distributor, in a plane perpendicular to the rotational scanning. The distributor thus has to be removed from the shaft for flat scanning, and the scanning polylines resulting from rotational scanning cannot be merged with polylines developed in flat scanning.

5.2.1 Exterior Scanning

In order to collect the exterior surface data, rotational scanning is used to scan the distributor. It is easy to mount the object along the A-axis because the hollow center can be used to support the whole piece. A wood shaft is put through the dowel of the A-stage and, and on it the distributor is mounted as well. Figure 5-2 is a picture shows this set up. To prevent the part from sliding, hot glue is used to attach the shaft and distributor. The heavier end of the distributor is attached near the machinery to reduce bending caused by the gravity. The distributor is made of metal, so it is coated with a thin layer of baby powder before scanning to reduce the odd reflection caused by its shiny surface.

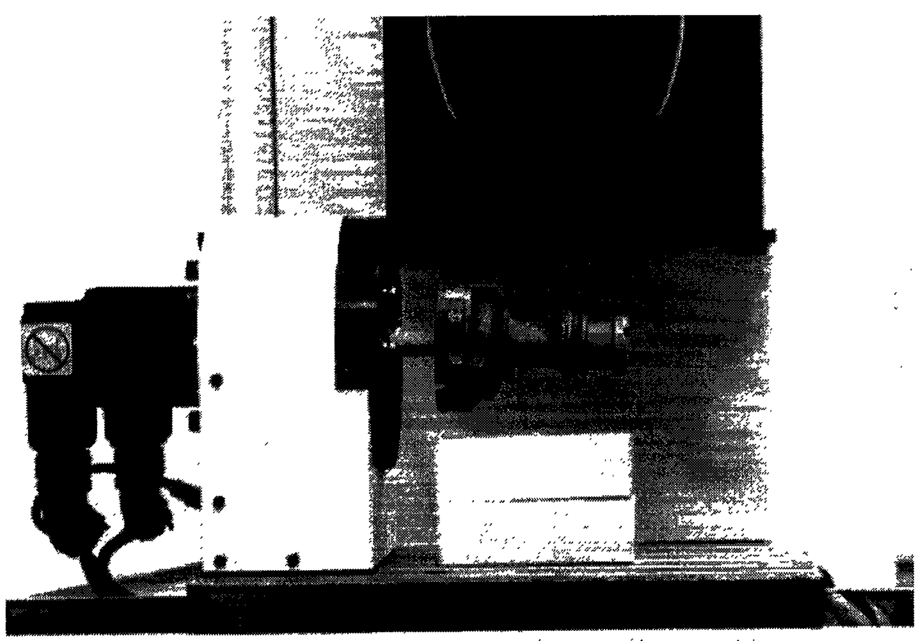


Figure 5-2 The Preparation for Exterior Scanning

Although only rotational scanning was employed to scan the exterior, three consecutive rotational scanning windows were created to scan the whole distributor. A rotational scanning window with smaller line increments was set at both of the two ends of the distributor. It is recommended to use smaller distances between scan traverse at an end of a specimen to collect an accurate length of the object. The point density of each cross-section is kept the same in the three rotational scanning windows.

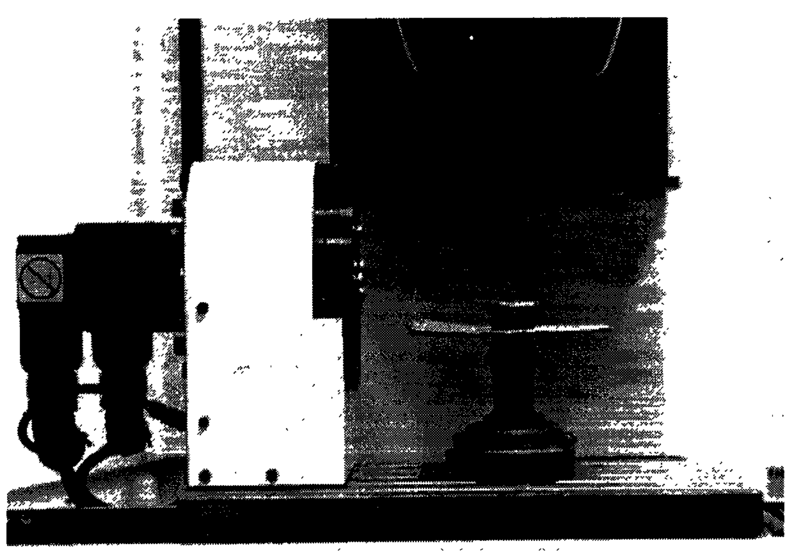
The largest section of the distributor, the mid-section, is scanned at a lower resolution, i.e., greater distance between two lines, to minimize the size of the scanning file and shorten the time need for scanning. File size is also increased when an edited scanning file is converted into a .stl file. Since there are no concave features on the exterior of distributor, combined scanning is not used. Because only the rotation scanning is employed, the distributor is detached from the shaft for flat scanning.

5.2.2 Interior Scanning

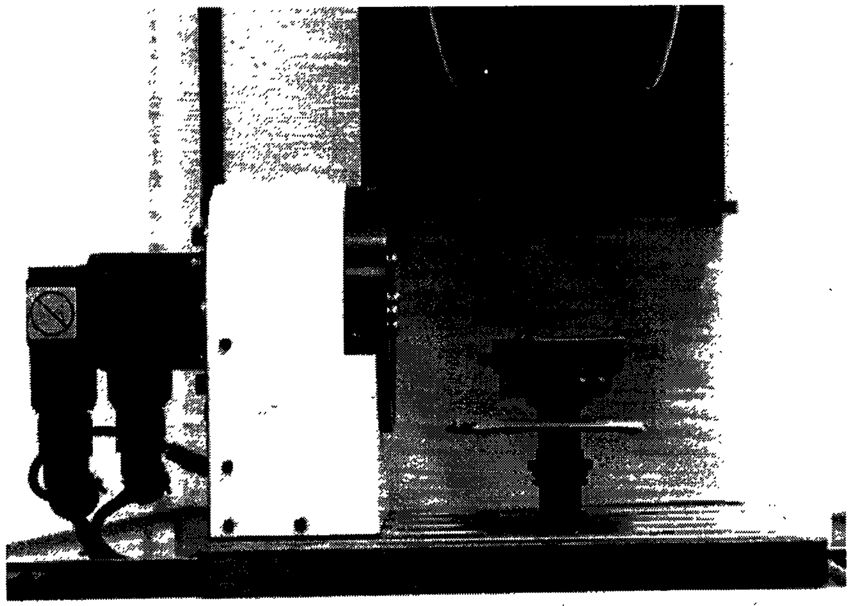
A flat scanning window was created for the top and bottom of the distributor. For this, the distributor was put on the platform and attached by glue. Figure 5-3 shows the preparation for scanning the top and bottom of the distributor. To the top and bottom, the same point density and line density is specified for the two flat scanning windows.

There are some screw holes on the top of distributor, so a flat paper board was conveniently attached under the top section. The purpose of the paperboard is to shorten the amount of z-search of laser head, and save time. Without the paperboard, the laser ray would shine through the screw holes of distributor and reach the platform, but still be unable to acquire a data point, where it is programmed to do. This would cause multiple "z-search" and require a longer time to move the laser head up and down to focus. A little modeling clay was inserted into the hollow cylinder, and that helped to save scanning time.

The two flat scanning windows are not meant to be combined, so the distributor may be put anywhere on the platform. Line distances between flat scanning and rotational scanning may differ, but the surface data from flat scanning and rotational scanning needs to be merged together to form a complete object. However, in this case study, the data processing of these scanning window differs from that of combined scanning, because the scanning data of exterior and interior is collected from different orientations of the distributor with the laser scanner.



(a) The preparation for scanning the top.



(b) The preparation for scanning the bottom.

Figure 5-3 The Preparations for Interior Scanning.

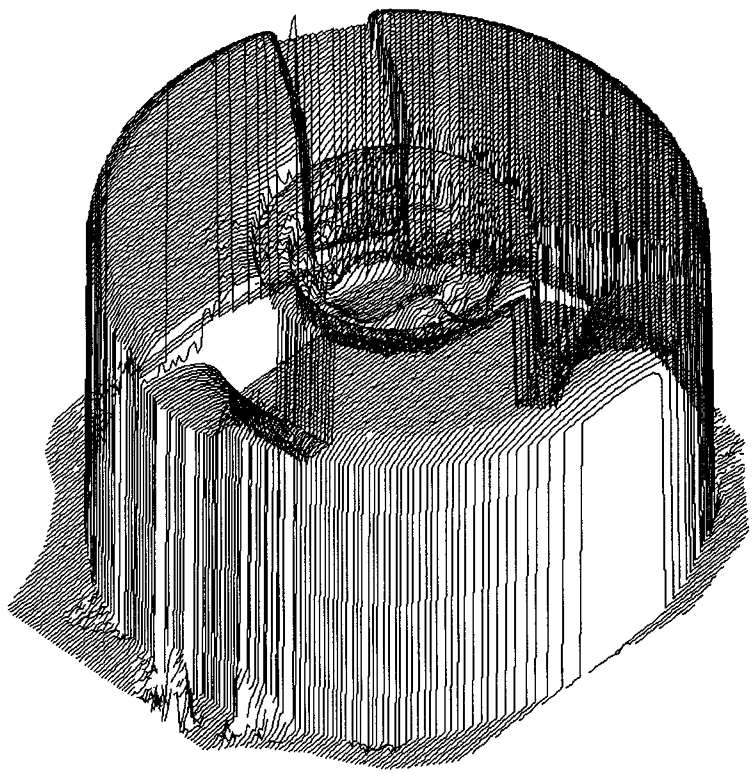
5.3 Data Processing

The exterior of the distributor is scanned in rotational scanning and its interior is scanned in two different flat scanning passes. This means that the data from different scanning windows has to be edited individually and they cannot be blended into a single file for editing in DataSculpt. After the editing work finished, the three final edited scanning files are converted into .stl files and all of them are merged together to form a single file for the reconstruction process.

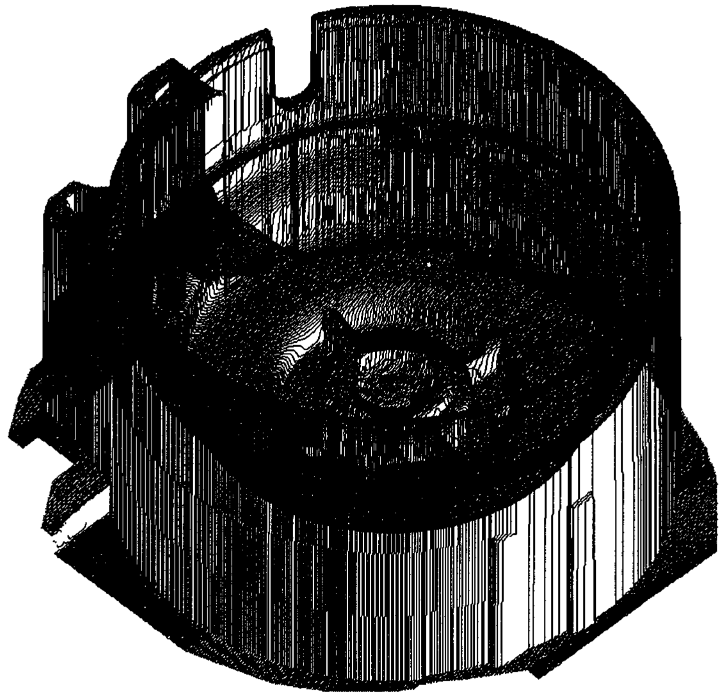
5.3.1 Data Editing

The original scanning data from different scanning windows was loaded into DataSculpt for editing. Figure 5-4 shows the raw scanning polylines of the distributor before editing. The whole rotational scanning polylines were composed of three scanning sections, two ends and a mid-section, and they were saved as a single scanning(.scn) file. Editing work on each scan file was conducted individually because the two flat scanning files were not surface data of the exterior.

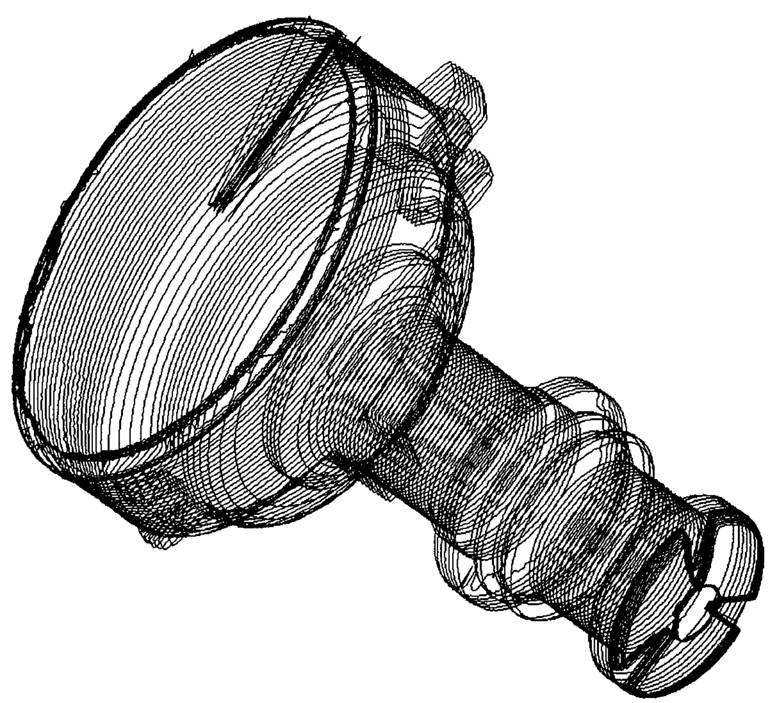
In this test case, the main job of editing was to delete the sections which are "fall-off" from the circular edge of the end piece to the platform or paper board. Figure 5-5 shows final edited scanning polylines of the distributor. Editing these three scanning files were much easier than that of combined scanning, because there is only one layer in each file. The final edited scanning files were converted into mesh files and then .stl files.



(a) Top view (Actual maximum diameter: 39.55mm).

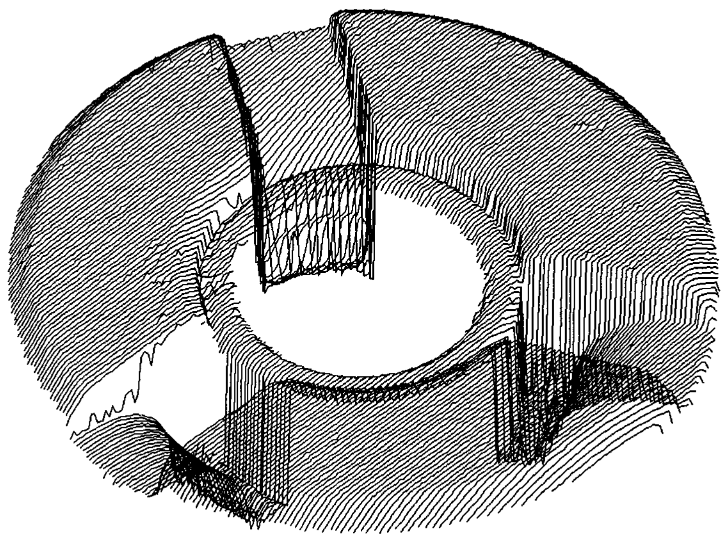


(b) Bottom View (Actual maximum diameter:93.60mm).

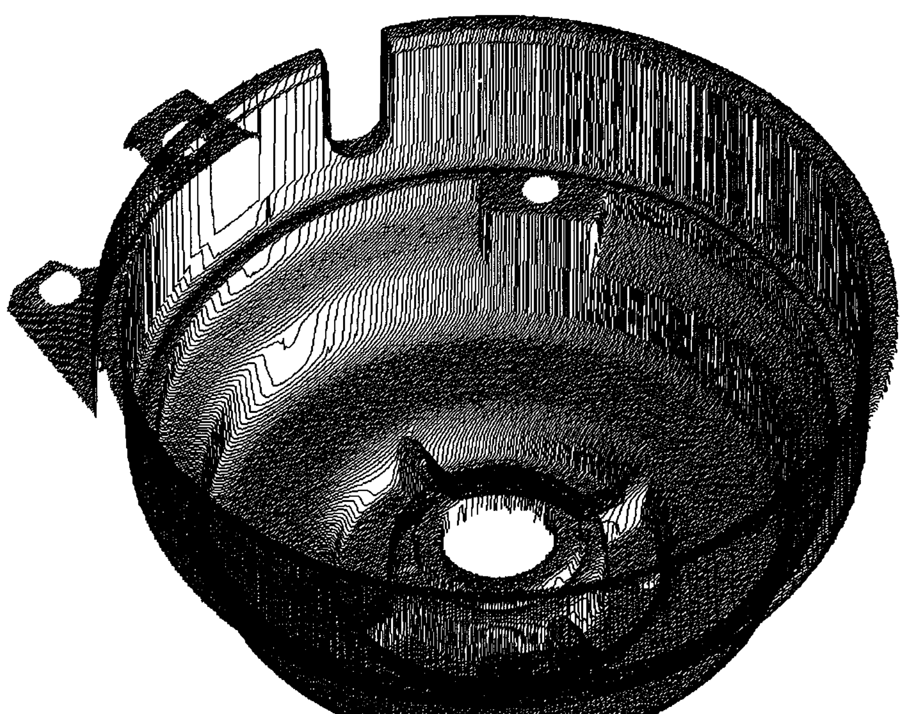


(c) Exterior (Actual length: 131.29mm).

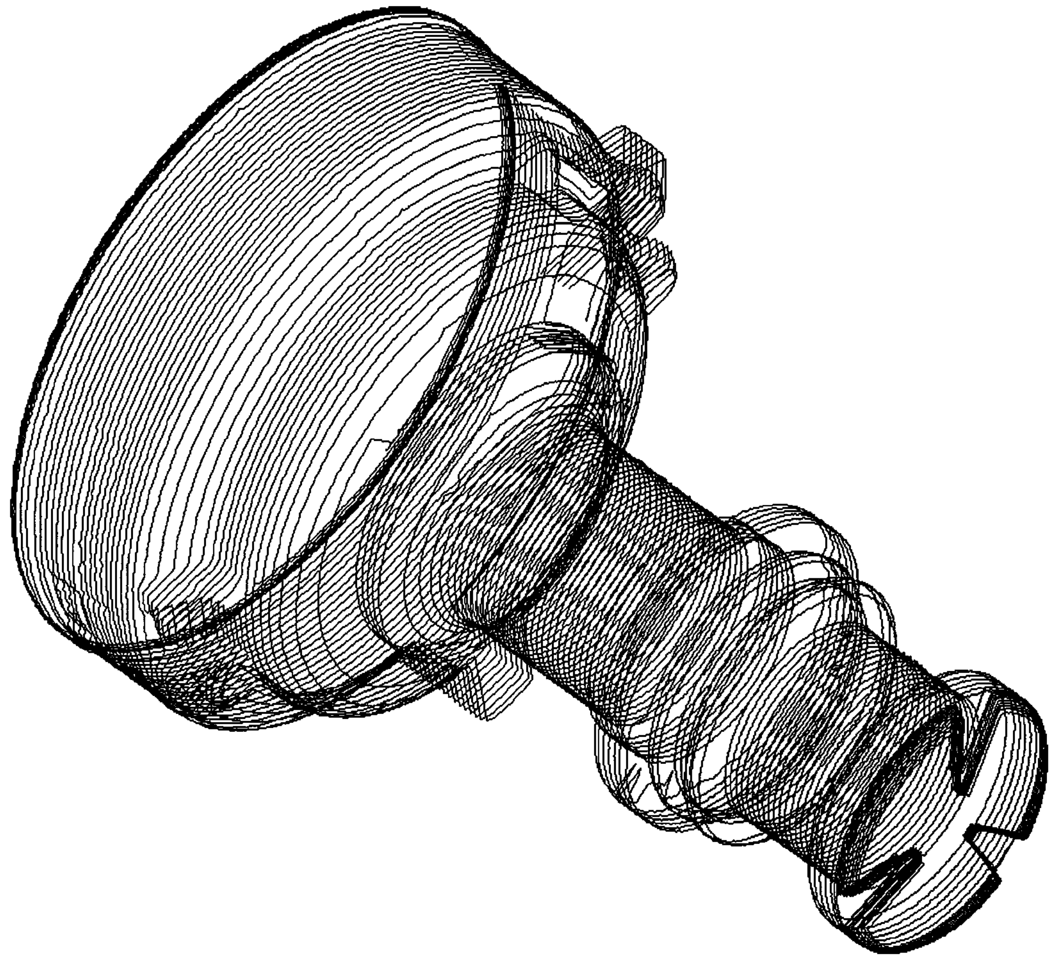
Figure 5-4 Original Scanning Polylines Before Editing.



(a) Top view (Actual maximum diameter: 39.55mm).



(b) Bottom view (Actual maximum diameter: 93.60mm).



(c) Exterior (Actual length: 131.29mm).

Figure 5-5 Final Edited Scanning Polylines.

5.3.2 Data Merging

The three .stl files derived from DataSculpt were loaded into Maestro for analysis first. After the files had been verified and fixed by Maestro, they needed to be merged into a single .stl file before using Maestro to generate the four files(.l, .prm, .r and .v) needed for building in the SLA-250. Magics RP, provided by Materialise, Inc., was the software used to merge the three .stl files together. On both top and bottom of the distributor, there are screw holes or gaps to be used as reference points for alignment.

The .stl file of the exterior was made a solid after the analysis using Maestro. The scanning file of the exterior created the boundary of the distributor, only a shell which was infinitely thin. Maestro was used to make the thin shell a solid by creating triangles to close the open ends. The .stl files of the top and the exterior were aligned and matched at the reference points, but in order to manipulate the objects in Maestro both had to be solids. Figure 5-6 is the rendering image to show the alignment of the two .stl files before matching.

Figure 5-6 Rendering Image of the Alignment of Two .stl Files

The .stl file of the top was extruded to form a solid volume. Afterwards, the .stl file of the body of the distributor was subtracted. After subtraction, the closed end of the distributor was cut, such manipulation may leave it open. Consequently, the boundary of the top end became undefined. To recovered the boundary, the extruded .stl file of the top was merged with the subtracted .stl file of the exterior. Then, the newly merged .stl file was merged with the .stl file of bottom, and the same steps were used to connect those two .stl files.

To create the hollow section of the distributor, a .stl file of a cylinder having the same internal diameter of the distributor was created using Pro/ENGINEER. Then, the .stl file of the cylinder was merged with the hollow to provide the inner boundary of the distributor. After a new single .stl file was completed, the file was loaded into Maestro for analysis. Figure 5-7 shows the rendering image of the final merged .stl file.

The function of analysis is to fix gaps, incorrect triangles, and incorrect normal direction. The merged .stl file was fixed using Maestro, and all the features of both ends were covered with new triangles. Because the two original .stl files of interior were only thin layers, they were not the .stl files forming solid objects. Even with extrusion and merging, the final .stl file, before analysis, still consisted of open shells which would be fixed by adding triangles in the process. However, the triangles generated by Maestro caused blocks to cover all the features of the interior and the hollow cylinder. The analyzed .stl file was loaded into Magics RP to delete those redundant triangles but the triangles were regenerated again when it was analyzed by Maestro.

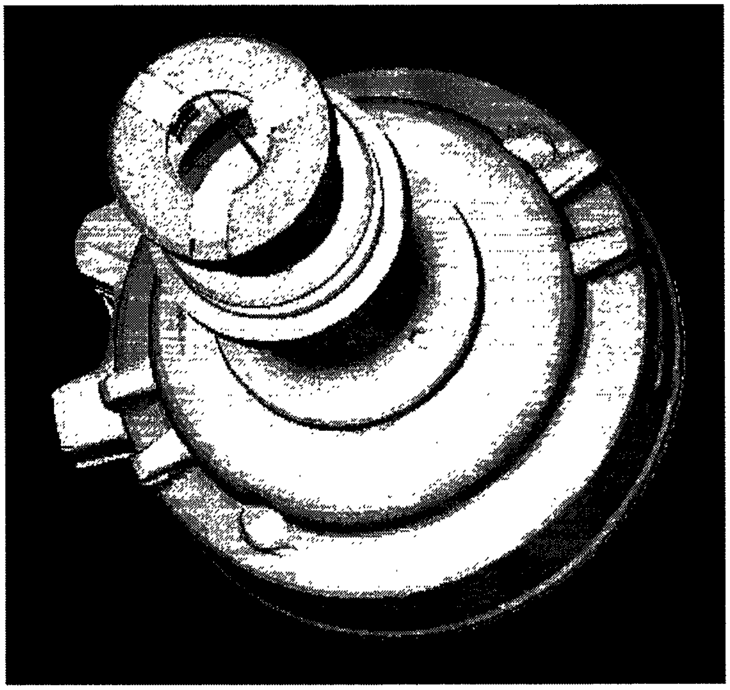


Figure 5-7 Rendering Image of the Merged .stl File

It is necessary to carry out the analysis process to generate the four necessary building files for the SLA-250, because Maestro cannot create supports for a .stl file with an open shell and/or gaps. With an inappropriate .stl file, Maestro is capable of fixing opening shells and gaps by adding triangles. Maestro continues to create supports and prepare the building files. However, in this study, the merge of the four .stl files was done by Magics RP. The software system, for some reason, is not compatible with Maestro. The added triangles by Maestro corrupt the features of the distributor. This leads to distortion of the object geometry. Further investigation is needed in this area to explore a more efficient and effective method to overcome the difficulties raised in this thesis work.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

The main objective of this thesis research is to design a system for object reconstruction. Recognizing the importance to capture details of the surfaces of the object, the system design begins with an innovative methodology for data acquisition. Implementation of the designed system is accomplished using the state-of-the art information-systems and the advanced rapid prototyping technology. Significant contributions of this thesis research are summarized as follows:

1. Laser scanners are powerful tools to carry out digitization with high accuracy and efficiency. However, an efficient data acquisition process relies on the technique used for scanning. This is extremely important when scanning objects with concave surfaces or protrusions, such as natural objects where the surface topography is characterized by geometric complexity. Presence of overshadow areas during scanning poses difficulties in collecting detailed information on the concave surfaces. The unique contribution of this thesis research is the development of a combined rotational and flat scanning technique for the data acquisition of natural objects. It collects the surface data which, in general, are difficult to collect. It should be pointed out that

data acquisition of certain types of overshadowed areas still remains as a new challenge to the research community as a whole.

2. A successful system integration is the key for object reconstruction. The Surveyor 3000 used in this study represents a powerful and efficient tool to capture the geometric complexity of the object. This approach is unique for natural objects where prior documentation, such as blue prints, never existed. The application of stereolithography to make duplicates of the object directly from an edited scanning file, and the free form fabrication process, highlights the achieved level of dimensional accuracy. The digital reconstruction of natural objects using the SLA-250 really opens a new research direction for paleontology. The integration of Surveyor 3000 and SLA-250 provides an efficient technique for reconstructing an object using laser technology and stereolithography.

3. The software aspect of the integrated system design, or the CAD environment, is composed of DataSculpt and Maestro. Although compatibility is always an issue, significant progress has been made to use all the three software systems for creating the necessary files required by the building process. The .stl files generated by DataSculpt are processed by Maestro. They are then converted into the four files(.l, .prm, .r and .v) needed for the SLA-250. The DataSculpt system offers capability to reassemble broken fossil pieces and complete the object construction file using mirror imaging. The Maestro system is capable of verifying the validity of .stl files and fixing open ends in the .stl files if they

exist. The compatibility among these software systems is beneficial to this reconstruction system design.

4. The most important contribution of this thesis research is the successful product realization of the fossil *Homunculus,* a facial skull and jaw. A batch production of duplicates will also be successfully completed. Exchange of these duplicates among scientists around the world will further explore unresolved mysteries in understanding the evolution of New World Monkeys. It is expected that the developed digital reconstruction methodology will have great impact on promoting scientific study in zoology and paleontology.

6.2 Recommendations for Future Work

A few recommendations are proposed to improve the final product manufactured by this reconstruction system.

1. An innovative fixture mechanism is recommended. The mechanism should be able to hold the specimen and rotate it along the Y- and Z-axes of the Surveyor 3000. In addition, such a fixture mechanism should hold the specimen without damaging its surface, and it must minimize the overshadowing effect caused by holding gears. For the best fixture design, the mechanism should reduce the vibration caused by the movement of the machinery. In the current setup of Surveyor 3000, the fixture used can only rotate a specimen along the X-axis to scan it, and the presence of overshadowed areas can not be avoided during scanning from this direction. Availability of such a new fixture mechanism

will allow the machinery to rotate the specimen along the Y- or Z-axes during scanning. Consequently, the laser beam will scan the overshadowing areas which are not accessible by rotating along the X-axis only. Following the improvement in hardware, efforts are also called for to further improve the capability of the scanning software and DataSculpt to ensure that the angles of rotation along the Y- or Z-axes for laser scanning can match the rotating angles along the Y- or Z-axes in DataSculpt for editing work.

2. The development of an innovative method to generate blueprints of an object from scanning data is highly recommended. The data may be acquired either with the Surveyor 3000, or from the .stl files generated by DataSculpt or Maestro. As demonstrated in this thesis work, data transformation from the scanning data to the .stl files for making duplicates is workable. However, data transformation from the scanning data to the generation of blue prints remains unsolved. A software package or a program should be developed to implement such data transformation for generating blueprints of the scanned objects.

3. Development of an innovative metrology to evaluate the accuracy of duplicates through the reconstruction process is recommended. No effort has been made to check the accuracy of duplicates made in this thesis research with respect to size and shape of the original fossil fragments. All evaluations are simply visual inspections. It should be pointed out that no effort has been made in making duplicates from the fossil fragments as what has been accomplished in this thesis research. The recommended development of such a special

metrology should be accomplished through an interdisciplinary effort among scientists and engineers to ensure that correct interpretations of the features of the fossils will be incorporated in the metrology development.

4. There is a reserved space within the laser head of the Surveyor 3000. It is for the users to install some instruments which are helpful for the machine's operations. A new technology should be developed to use photographs to create scanning windows and set up the z-search. A camera may be installed in the laser head to take pictures of the scanned objects. Before starting the scanning work, these pictures can be used to automatically create the scanning windows and set up the value of z-search. It can help save time to create scanning windows and shorten the scanning and editing process.

REFERENCES

Aronson, R. B., "Forward Thinkers Take to Reverse Engineering," Manufacturing Engineering, November 1996, pp. 34-44.

Bailey, M. J., "Tele-Manufacturing: Rapid Prototyping on the Internet," IEEE Computer Graphics and Applications, November 1995, pp. 20-26.

Jacobs, P. F., "Stereolithography and other RP&M Technologies from Rapid Prototyping to Rapid Tooling," Society of Manufacturing Engineers, 1996, pp. 1-77.

Jacobs, P. F., "Rapid Prototyping & Manufacturing Fundamentals of StereoLithography," Society of Manufacturing Engineers, 1992, pp. 397-422.

Rosenberger, A. L., "Evolution of New World monkeys," The Cambridge Encyclopedia of Human Evolution, Cambridge University Press, pp. 209-216.

Subbacharya, M. M. V. "Reverse Engineering of Complex Shapes Using a CMM," M. S. Thesis, University of Maryland, Baltimore County, Baltimore, MD, 1991, pp.1-7.

Szalay, F. S. and Delson, E., "Evolutionary History of the Primates," Academic Press, Inc., New York, 1979. pp. 298-300.

Tattersall, I. and Sawyer, G. J., "The skull of "Sinanthropus" from Zhoukoudian, China: a new reconstruction," Journal of Human Evolution, Academic Press Limited, (1996) 31, pp. 311-314.

Zollikofer, C. P. E. and deLeon M. S. P., "Tools for Rapid Prototyping in the Biosciences," IEEE Computer Graphics and Applications, November 1995, pp. 48-55.