

**Integration of Rapid Prototyping and Reverse
Engineering for Complex 3D Shape Design**

by

David W. Robinson

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Signature of Author _____
Department of Mechanical Engineering
May 31, 1996

Certified by _____
Professor David C. Gossard
Professor of Mechanical Engineering

Certified by _____
Professor Emanuel M. Sachs
Professor of Mechanical Engineering

Accepted by _____
Ain A. Sonin
Chairman, Department Committee on Graduate Students

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Abstract

The design of complex 3D geometry is a vital part of engineering practice today. Industrial designers utilize shape as a key element of product differentiation. For functional parts, the design of complex shape is an important tool for achieving high performance at low cost. While CAD tools are effective at the precise specification of 3D shape, they are not effective tools for the exploratory phases of design where the general shape is defined. For this reason, the creation, inspection, and manipulation of physical models plays a crucial role in the design process. Both physical and computer models are necessary in the design of complex 3D geometry.

Currently, designers use an ad-hoc combination of physical and electronic models. This thesis creates a system, a design cycle, wherein a designer can manipulate either physical or computer model and can readily translate between the two. The translation from computer to physical is done using a rapid prototyping technique called Three Dimensional Printing. A designer can then use hand tools to form the model by carving, shaping, and joining additional material. The physical to electronic translation is done by a layered digitizing method called Deconstruction and semi-automated software tools are used to create a CAD polygonal solid model. Conventional CAD tools are used to manipulate the electronic model and the cycle can be repeated as necessary.

This system provides a fluid approach to the design of 3D complex shape which can be used for a wide range of applications. This thesis describes four applications in detail as well as fully demonstrating the design of a complex sculptured razor handle.

Thesis Advisor: David C. Gossard
Title: Professor of Mechanical Engineering

Thesis Advisor: Emanuel M. Sachs
Title: Professor of Mechanical Engineering

Dedication

This thesis is dedicated to my family.

To my parents
for preparing me and sending me on the path.

To my wife
for walking with me and supporting me on the journey.

Acknowledgments

I want to express my deep appreciation to the many people that have helped me in this research and made it possible for me to finish.

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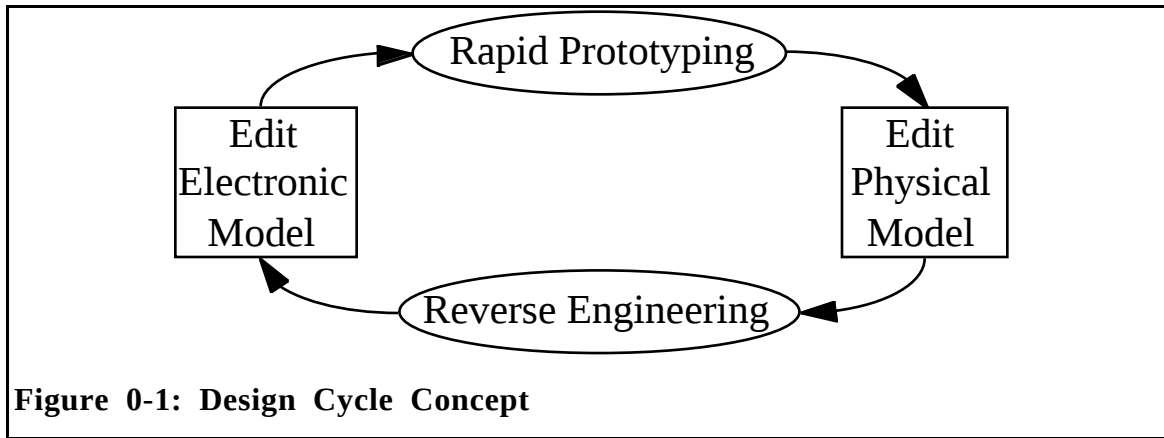
0. Executive Summary

0.1 Motivation

The ability to rapidly produce the designs of parts and objects with complex 3D geometry is a basic necessity in today's market place. Often, designs combine the requirements of free form shape and functional constraints into one piece. Currently, the design of complex 3D shape is an adhoc mixture of methods involving both physical and electronic models. Each method serves a different need. Physical models are useful for subjective design (i.e. aesthetic or ergonomic design) where the "feel" is examined and where complex interplay between geometry and assemblies can be visualized. On the other hand, electronic models are well suited to the precise, mathematical specification of shape. A difficulty arises in the fact that the information and knowledge gained from one model is often lost while trying to move onto the next stage of design.

In order to aid in the translation between the electronic world of modeling and the physical world, two technologies have emerged: rapid prototyping and reverse engineering. The goal of rapid prototyping is to use a computer model and create a physical model quickly and directly with little human interaction. Reverse engineering tries to automatically generate a computer model from an existing physical one. Each technology tries to capture information available from the design in one medium and translate that into the other.

Integrating rapid prototyping and reverse engineering into a continuous cycle which can repeat itself indefinitely would allow designers the ability to design in the medium which would best realize their concepts. The advantages of both modeling worlds could be exploited and the disadvantages could be avoided or neglected. Figure 0-1 shows the idea of the design cycle.



Being able to use both of these models allows the designer more time actually designing and less time worrying about how to create, explain, and communicate ideas. With a cycle in place that maintains information gained in each step of the design, there will be no fear of losing information in model transition. This should give designers more opportunity to quickly work out all the details of everything they have imagined and envisioned.

0.2 Goals

This research has three goals that have been achieved and are fully described in the thesis.

1. Build a Design Cycle – Build or bring together all tools and pieces necessary for use in the design cycle.
2. Find Applications – Come up with realistic applications where the design cycle could be used and would be an improvement for a current situation.
3. Demonstrate Applications – Use the design cycle to demonstrate functionality and usefulness.

0.3 Results

0.3.1 Building the Design Cycle

A rudimentary design cycle has been realized. It contains all the necessary components to continually interchange physical and electronic models. Several parts of the existing design cycle which involve the translation from one medium to the next are still manual, meaning that there is a great deal of human interaction. However, many of the actions done by the user right now, in theory, can be automated. High level decisions will always need to be made by the user, but much care has been taken to insure that mundane tasks can be automated.

0.3.2 Applications

Many of the applications are described here in a short list.

1. Subjective geometry (i.e. aesthetic, ergonomic) which also has geometric or kinematic constraints.
2. Visualization and design of assemblies.
3. Design and redesign of new or existing parts.
4. Required shop floor modifications can be directly incorporated into the computer model.
5. 3D Fax Machine.
6. Medical visualization and creation of prosthetics and orthotics.
7. Cosmetic, reconstructive, and orthopedic surgery.
8. Creation of computer models for graphics, rendering, and entertainment.
9. Uniform textures on complex geometries.

0.3.3 Demonstration

The first application on the list is demonstrated by designing a complex sculptured razor handle as seen in Figure 0-2. The razor is blocked out roughly in CAD and a physical model is made. A designer then carves and shapes the handle using a simple carving knife. When modifications are satisfactory, the part is digitized and a polygonal Brep CAD model is created from the digitized data. This CAD model is then unioned with a razor head that is made from prismatic shapes and the design is complete.

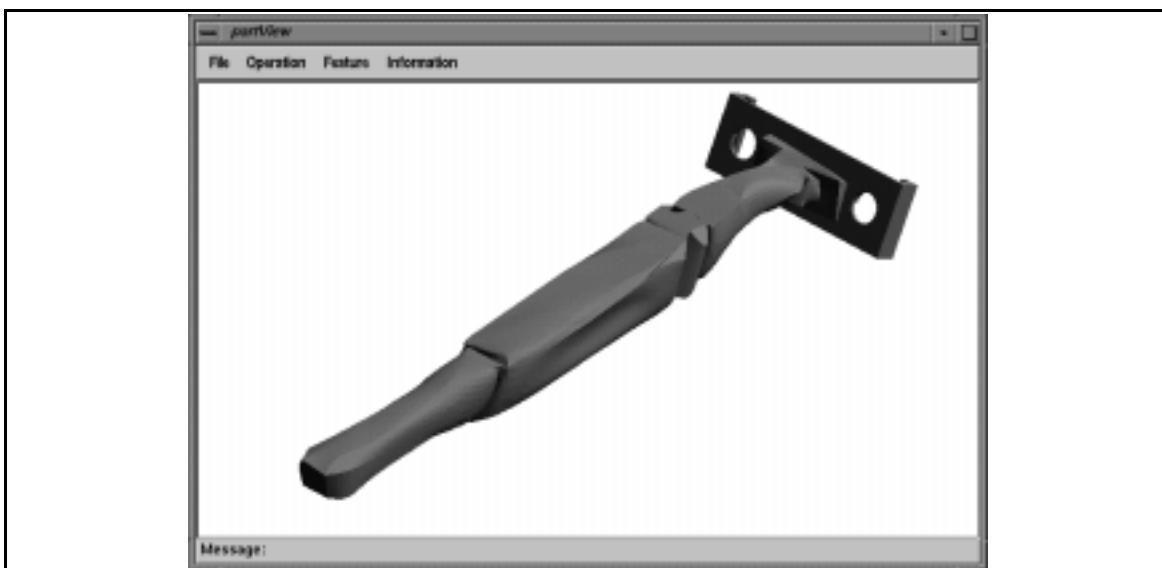
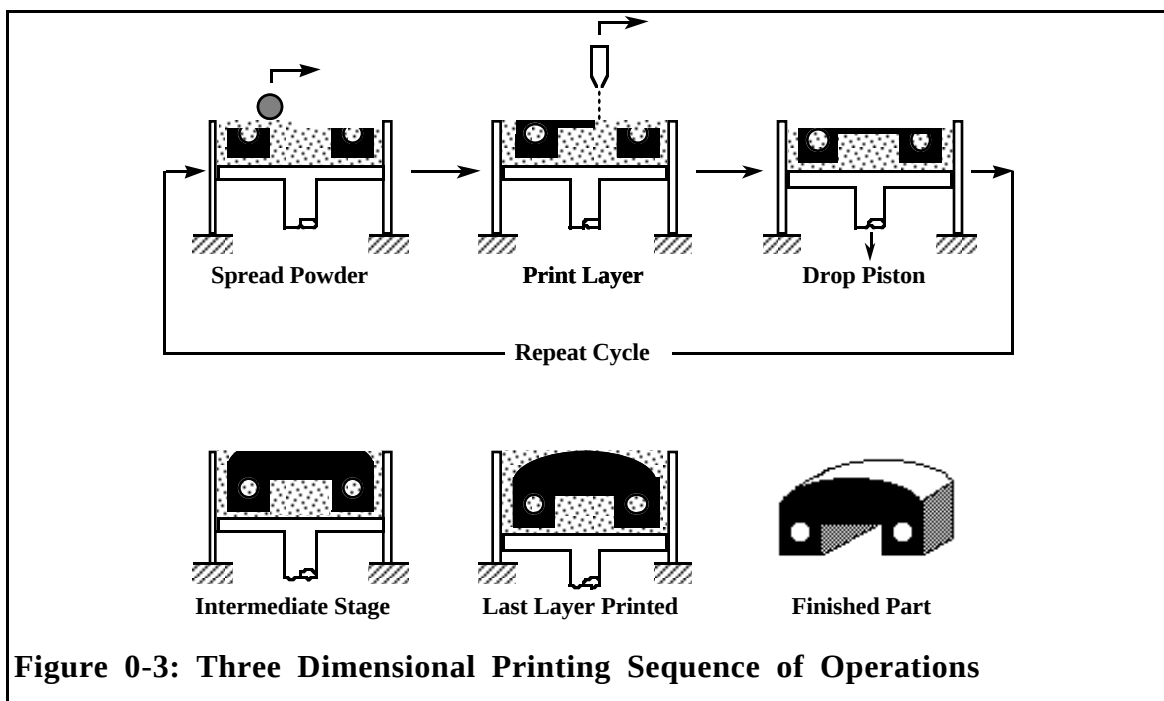


Figure 0-2: Complex Sculptured Razor Handle – Demonstration of the Design Cycle

0.4 Methods

In order to test the design cycle, various pieces from the fields of rapid prototyping, reverse engineering (digitizing), and CAD are built, compiled and assembled. The translation from electronic model to physical model is done using a rapid prototyping method called Three Dimensional Printing (Figure 0-3). 3D Printing is one of the most flexible of all the rapid prototyping techniques. The process can create parts of any geometry. The support gained from the powder bed means that overhangs, undercuts and internal cavities can be created automatically without the need for building special support structures simultaneously with the part.



Since 3D Printing has use with a wide range of materials, many material combinations are tested and a prototyping material suitable for physical handling (i.e. carving, sanding, joining, machining, etc...) is created. The recommended prototyping material is a composite of soda lime glass powder and bees wax. 3D printing joins the glass powder using an acrylic binder called acrysol and the part is infiltrated with the bees wax in a secondary operation.

As mentioned before, the prototyping material can be altered in various ways such as carving, sanding, joining, and machining. A designer can physically change and modify a part and when satisfied with the modifications, the part can be digitized using a layer by

layer slice and scan method called deconstruction. Figure 0-4 shows the deconstruction process.

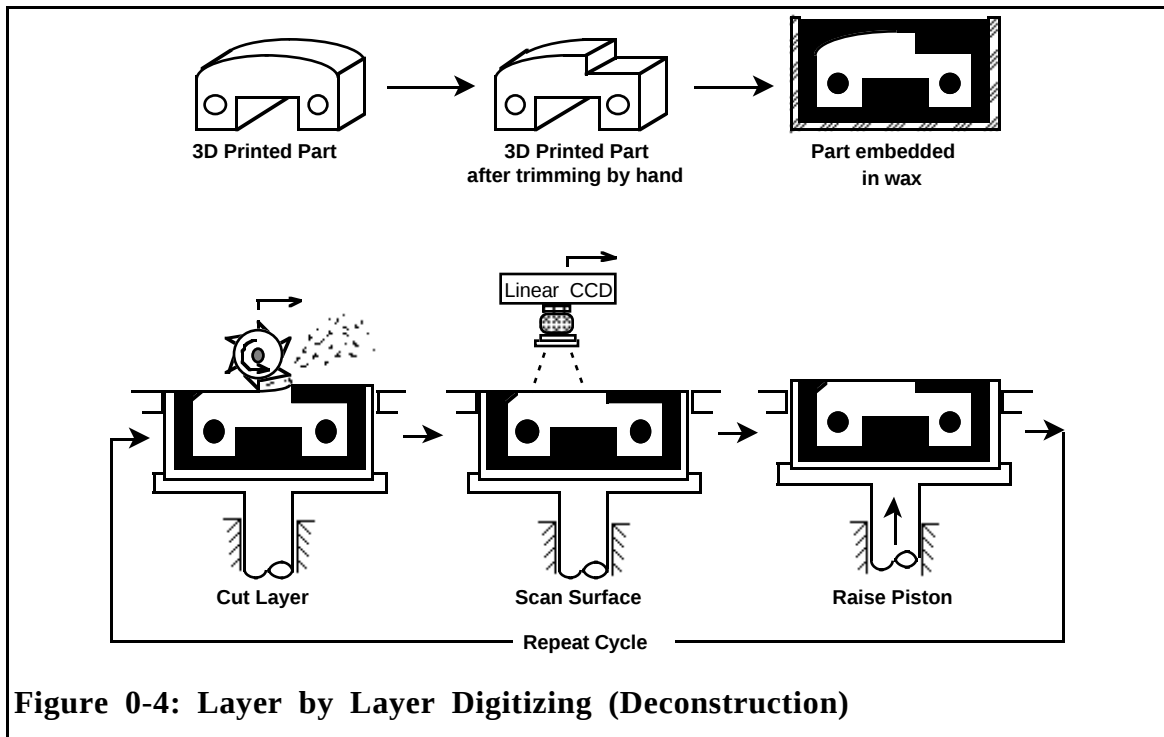


Figure 0-4: Layer by Layer Digitizing (Deconstruction)

Deconstruction is essentially the reverse method used to create the part by 3D printing. Before milling, the part is embedded in paraffin wax with a carbon black dispersion. This provides optical contrast to the part during imaging as well as support for the part during milling. Deconstruction has a one time setup and can image any geometry, even parts with internal features. The images capture the geometry of the part in a discrete voxel-like manner.

Boundary points for the surface of the model are found using a 3D edge-detection algorithm and the surface point data is converted into a polygonal Brep CAD model using published as well as custom algorithms. This CAD model can be manipulated using custom software (user interface shown in Figure 0-2) and a CAD library to perform Boolean operations. This model can also be exported to the rapid prototyping machine and the cycle can continue indefinitely.

0.5 Future Work

The existing design cycle is not a perfect system yet it is functional in its present state. A few parts of the system are very user friendly but unfortunately others or not. Nevertheless, the design cycle is now in a state where it can be explored and optimized. Better tools can be found or developed and the time required to translate between modeling mediums can be reduced. There is still much work that can be done to improve it. Here is a short list of areas for future work.

1. Shape Features – Add capability to the CAD software to recognize and define shape feature such as planes, holes, and pockets.
2. Cycle Remembering – Develop tools to identify what parts of the digitized physical model differ from the original CAD model.
3. Wax 3D Printer – This rapid prototyping machine could have one of the fastest build rates in the rapid concept modeler market. It would also open up the possibility of exploring multi-color rapid prototyping by using a color printhead.
4. Automated Digitizer – Create and automated digitizing machine (Deconstructor) to help accelerate the reverse engineering process.
5. Export for Manufacture – Develop a method to export geometry information into commercial applications manufacturing methods besides the .STL polygonal format.

Even though there is still work to be done, the design cycle shows promise a powerful new design tool for complex 3D geometry.

Chapter 1

1. Introduction

1.1 Motivation

The ability to rapidly produce the designs of parts and objects with complex 3D geometry is a basic necessity in today's market place. Industrial designers utilize shape as a key element of product differentiation in almost every product of commercial interest. Functional parts also require complex shape for structural soundness and proper assembly under demands of low weight and material utilization.

Often, designers combine the requirements of free form shape and functional constraints into one piece. Currently, the design of complex 3D shape is an adhoc mixture of methods involving both physical and electronic models. Each method serves a different need. A difficulty arises in the fact that neither of these models nor their methods flow easily from one to the other. Physical models are useful for subjective design (i.e. aesthetic or ergonomic design). Examining "feel", performance, and manufacturability is best done with physical models. They are also useful for testing and visualizing the complex interplay between geometry and assemblies. On the other hand, electronic models are well suited to the precise, mathematical specification of shape. Holes must be round and planar surfaces must be planar. Scaling can also be done easily and exactly in electronic models.

Both models are useful for communication, albeit, in different forms. Physical models can communicate subjectively to the designer. The model can speak for itself as to the "right fit" or "right feel". Physical models can also prove assembly interference or tolerance. The computer model helps in reducing communication steps from design to manufacturing by eliminating the need for paper work such as full detail drawings done by hand. The drafter may accidentally make a mistake creating the drawings and a machinist may misinterpret

them. Computer models can only help in reducing communication errors between design and manufacturing.

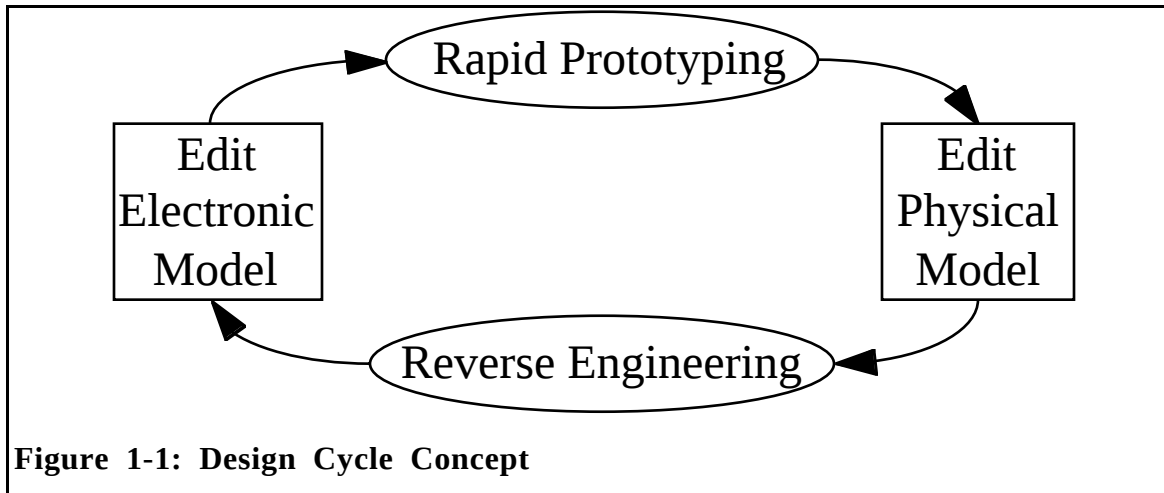
The greatest advantage of the computer model may be its ability to undo changes (erase). Previous versions of a model can be saved and retrieved. This gives designers great courage to try new options and ideas without being fearful of losing prior work. Physical models, once changed, are difficult if not impossible to retrieve.

In this ad-hoc mixture of designing with different models, the information and knowledge gained from one model is often lost while trying to move onto the next stage of design. This leads to increased design redundancy and decreases opportunity for design iterations. In order to aid in the translation between the electronic world of modeling and the physical world, two technologies have emerged: rapid prototyping and reverse engineering. The goal of rapid prototyping is to use a computer model and create a physical model quickly and directly with little human interaction. Reverse engineering tries to automatically generate a computer model from an existing physical one. Each technology tries to capture information available from the design in one medium and translate that into the other. Neither technology is perfect, but continuing research is constantly advancing both fields.

Rapid prototyping and reverse engineering constitute a one-step design jump from one medium to the other. Little thought, however, has gone into the idea of integrating these into a continuous cycle which can repeat itself indefinitely. Being able to do so would take advantage of the iterative nature of design. It would allow designers the ability to design in the medium which best suited to realize their concepts. The advantages of both modeling worlds could be exploited and the disadvantages could be neglected. This type of design cycle could be a powerful tool.

1.2 The Idea

Design is the creation of a physical interpretation for a concept that has not been expressed before. Both physical and electronic models are essential tools in that creation process. Recognizing that fact in its relation to the design of complex 3D geometry, an integrated system that can efficiently and economically take advantage of both modeling mediums is needed. In order to do this, not only must a designer be able to use both models but they must be able to translate quickly between them with no loss of information. Figure 1-1 shows the design cycle concept.



Being able to use both of these models allows the designer to spend more time actually designing and less time worrying about how to create, explain, and communicate their ideas. All of the good aspects of each modeling medium can be exploited. The physical models will help the designer use their subjective human skill and the electronic models allow the use of the computer's precision power. With a cycle in place that maintains information gained in each step of the design, there will be no fear of losing information in model transition. This should give designers the opportunity to reach the point of "EUREKA!" or serendipity that comes from working out all the details and clearly seeing everything they have imagined and envisioned.

1.3 Applications

There are many applications to the described design cycle. Below is a short list.

1. Subjective geometry (i.e. aesthetic, ergonomic) which also has geometric or kinematic constraints.
2. Visualizing and designing assemblies.
3. Design and redesign of new or existing parts.
4. Incorporating required shop floor modifications directly into a computer model.
5. 3D Fax Machine.
6. Medical visualization and creation of prosthetics and orthotics.
7. Cosmetic, reconstructive, and orthopedic surgery.
8. Creation of computer models for graphics, rendering, and entertainment.
9. Uniform textures on complex geometries.

Each of these and possibly many more fit into the model of the design cycle. A more thorough description of some of the mentioned applications along with examples are found in the Applications chapter on page 81.

1.4 Thesis Organization

This thesis is organized into eight chapters which describe the design cycle as a whole and each of its individual parts finishing with an explanation of applications and suggestions for direction of future work. Below a brief summary of each chapter.

1. Introduction – Describes the idea and motivation of the research by giving background material and a short list of applications. It also gives an overview of thesis organization.
2. Design Cycle – Covers the design cycle concept in more depth and surveys existing technologies. This chapter also reports on the results of the research.
3. Rapid Prototyping – Three dimensional printing is the method chosen to explore the design cycle. Challenges and solutions for rapid prototyping are explained.
4. Edit Physical Model – Evaluates the prototyping material as a physical modeling medium.
5. Reverse Engineering – A new method of reverse engineering is described and implemented.
6. Editing Electronic Model – Software tools which semi-automate the generation of a useful CAD model are described and implemented. Traditional computer modeling tools are used to modify the CAD model.
7. Applications – The design of a complex sculptured razor handle is demonstrated and other selected applications are fully examined.
8. Future Work and Conclusions – Describes the direction that the research should take.

Is the conceived design cycle useful? That is the question this thesis attempts to answer. While this research is by no means complete, the answer to the question is “Yes”. This thesis also details some of the technical issues of the research that were solved in order to put together a rudimentary design cycle. Future avenues for research are also explained which have come from unanswered or new questions discovered in the course of this work. The design cycle, as described in the next several chapters, shows promise as a powerful new tool for design.

Chapter 2

2. Design Cycle

2.1 Survey of Existing Technologies

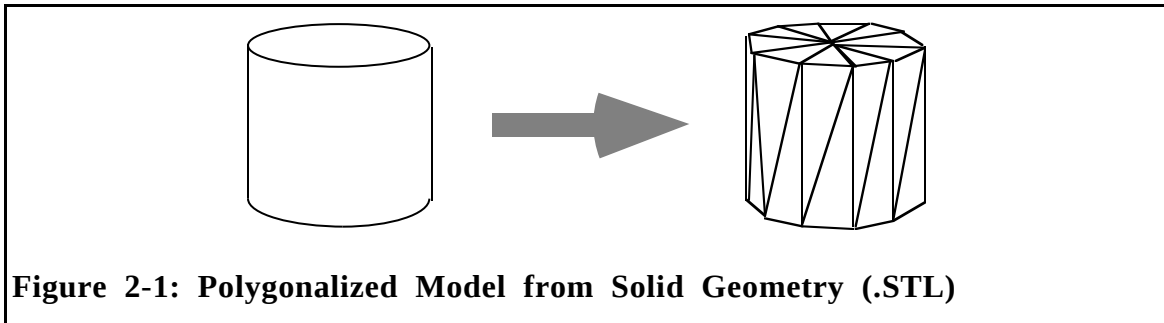
In order to better understand the various pieces of the design cycle, a partial survey of existing technologies for rapid prototyping, modeling materials, reverse engineering, and CAD systems are explained.

2.1.1 Rapid Prototyping

Automated generation of physical parts from computer models is not new technology. In the early 1950's, at MIT's Servomechanisms Laboratory, the first computer numerically controlled (CNC) milling machine was developed out of a program funded by the United States Air Force [Jaikumar]. Research continues to be done on CNC milling and it is still a valuable tool in the manufacturing arena. Currently, there is one major drawback to CNC milling; the time required for the user to generate instructions for the machine is quite extensive. In the last decade, however, engineers have developed several ways to create accurate physical representations of computer models which are not time intensive for the user – Rapid Prototyping. The major applications for this technology have been early verification of product designs and quick production of prototypes for testing. There is also interest in rapid prototyping for visualization, but it is currently difficult to cost justify. This may soon change as the industry continues to develop.

Most of these rapid prototyping technologies use layered manufacturing methods to create the models. The process starts with a computer model of an object. Typically the computer model is polygonalized into planar surface patches (see Figure 2-1). A computer model is then “sliced” into thin sequential cross-sections. From here, depending on the method, the cross-sections are rasterized or the contours are traced and the information is sent to the rapid prototyping machine. The machine builds the physical prototype layer by layer with

the layers ranging from 25 - 250 microns. Each cross-section is connected to the previous one.



As mentioned before there are several rapid prototyping techniques and different commercial companies which use these processes. The process that was used for the research in this thesis is called Three Dimensional Printing. It is a process developed at Massachusetts Institute of Technology and is described in full in the Rapid Prototyping chapter found on page 31. This survey does not cover all the benefits and drawbacks of each method but rather presents a few of the many methods for the reader's knowledge.

The most commercially successful product is stereolithography which is marketed by 3D Systems in Valencia, CA. This method uses a low-power ultraviolet laser beam that traces across a vat of photocurable liquid polymer and thus produces a layer of solidified resin. The vat is lowered incrementally by the height of the next slice, the layer is recoated with resin and another is traced on top of it. This cycle is repeated until the part is completed.

Even though stereolithography is a leader in the rapid prototyping market place, all other methods continues to mature and progress. Helisys Inc., in Torrance, CA uses a process called Laminated Object Manufacturing (LOM). This method cuts a cross-section of heat-activated adhesive coated paper with a laser. Layers are bonded together to form a finished part. The finished product looks like laminated wood and in essence is wood since its main material is paper.

Fused Deposition Modeling (FDM) developed by Stratasys in Eden Prairie, Minn. uses a heated thermoplastic and extrudes it from a nozzle positioned above an x-y table. Thin layers are built from the bottom up as the thermoplastic is deposited. With slight modifications to the operating parameters, one of the other materials such as investment casting wax can be used.

DTM of Austin, TX uses a process called Selective Laser Sintering (SLS). SLS rasters a powerful laser along a cross-section of heat-fusible powder and the powder sinters together. After forming a layer, new powder is added and spread across the just finished layer. The process repeats layer by layer until the completion of a finished part. Like FDM, by varying operational parameters such as the power and speed of the laser, different materials can be formed in SLS too. These materials range from plastics to metals.

The most applicable research to the design cycle is the development of rapid concept modelers or office rapid prototyping machines. (Current rapid prototyping machines are operated in a laboratory.) These new machines will help product designers and part designers who need quick concept models in the office which are safe (nontoxic), reliable, and inexpensive. 3D Systems (Figure 2-2), Sanders Prototype, and BPM Inc. have all introduced machines for this purpose. The method of manufacture for these office rapid prototyping machines are copies or variations of the previously described technologies. What remains to be seen is whether their cost effectiveness, ease, and reliability will be as claimed by sales, marketing, and advertising.

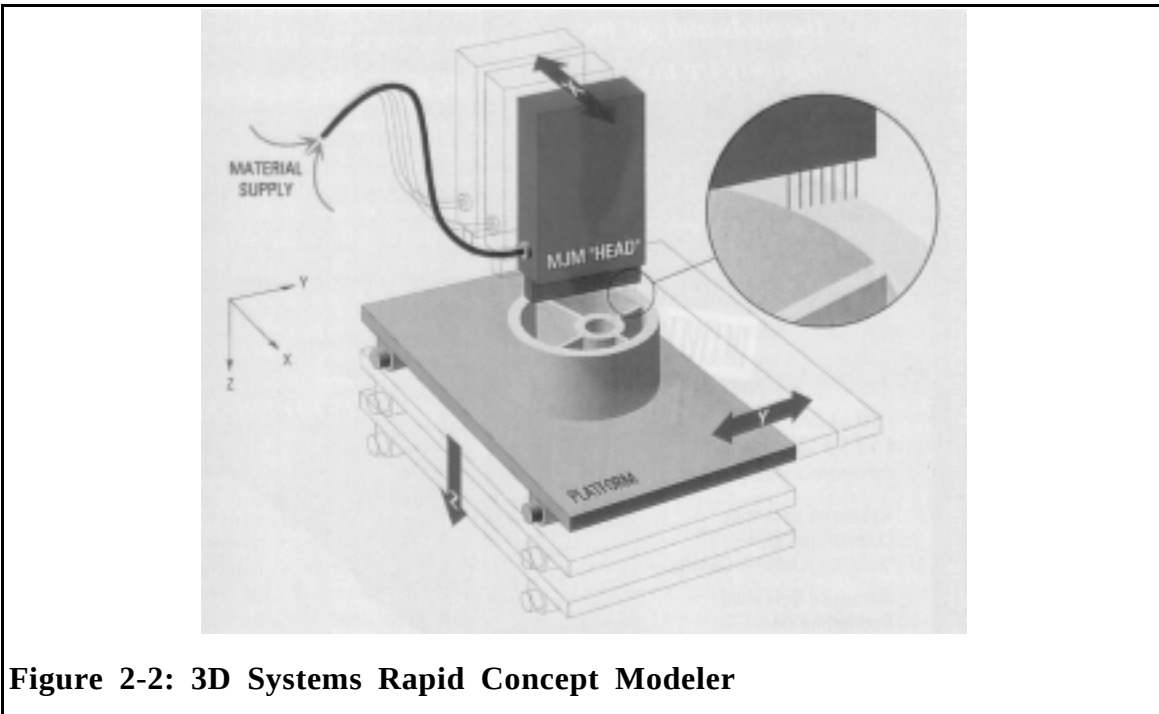


Figure 2-2: 3D Systems Rapid Concept Modeler

2.1.2 Modeling Materials

There are innumerable modeling materials used by designers today. Here is a short list of some of the more popular ones.

- Bluefoam
- bass wood
- polyurethane dense foam
- RenShape
- clay
- Wax

Bluefoam is a quick-concept design material. It is shaped most easily by a hot wire machine. Proficient model makers can create something in Bluefoam almost as quickly as they could draw something on paper.

Artists have always enjoyed working with clay. Clay has nice properties in that it can be formed and shaped with simple hand pressure. Wax can be formed in a similar fashion. The most common modeling wax is called Detroit wax. It is used in the car modeling industry especially for auto shows.

Three materials with similar properties are bass wood, polyurethane dense foam, and a new product from Ciba Geigy called RenShape. Each of them have nice carving properties and can be sanded to a very fine surface finish. They are structurally very solid as well. RenShape is becoming very popular among model makers. Pieces can be glued together to make large objects, but it is difficult to add small amounts of material. Further information about joining is found in section 4.1.3 on page 44.

Ideally, the material system developed for the Design Cycle would have all the good properties of easy-shaping materials like clay and wax and the structural integrity of the RenShape. The limiting factor is that it must also be a material capable of being formed in a rapid prototyping method, specifically in our case 3D printing. Using the desirable properties of clay and RenShape as a benchmark, different material systems were investigated and a satisfactory system was found.

2.1.3 Reverse Engineering

The most direct method for creating a mathematical or electronic model of an object is to take traditional measuring devices such as calipers, make measurements directly on the part, and subsequently record the information on paper or in a computer model. This requires extensive user input. Reverse engineering is the field of research involved with automating the process of creating computer models from physical ones. Automating the reverse engineering process traces its genealogy to the pantograph which is a mechanical linkage that can produce scaled versions of any arbitrary shape. More familiar pantograph like machines are the copy lathe and copy mill. A copy lathe moves a stylus along a 1D profile and a cutter produces a revolute object with the same profile. Similarly, a copy mill moves a stylus over a surface and the x,y,z information is copied to a 3-axis mill which makes a copy of the original item. An example of the 2-axis copy mill is a key duplicating machine.

There are many cases where geometry of highly complex objects is required and when high precision and a high number of measurements are needed. In these instances, 3D position digitizers such as contact and non-contact coordinate measuring machines (CMM) are used. Contact CMMs acquire data by physically contacting a probe with important points on the object. Very high accuracy is possible with this method but it is extremely slow and the geometries that contact CMMs can work on are limited. Non-contact CMMs can significantly decrease the time required for data gathering at the expense of accuracy. These machines project a line or a spot of light and use triangulation to calculate range. Companies that produce these machines, like Cyberware, Digibotics, and Laser Design claim accuracy of 0.002 inches. In practice, however, results show accuracy closer to .01 inches and noise can be generated which may be as much as a few feet away from the actual surface of the object. Data gathering is further complicated for range finders when they are used to completely scan an object using multiple views. These views must be merged together into a common data set and that is not a trivial problem. One solution to the view merging problem is to add another axis to the measuring frame and mount the object on a turntable like the small Digibotics scanner shown in Figure 2-3.

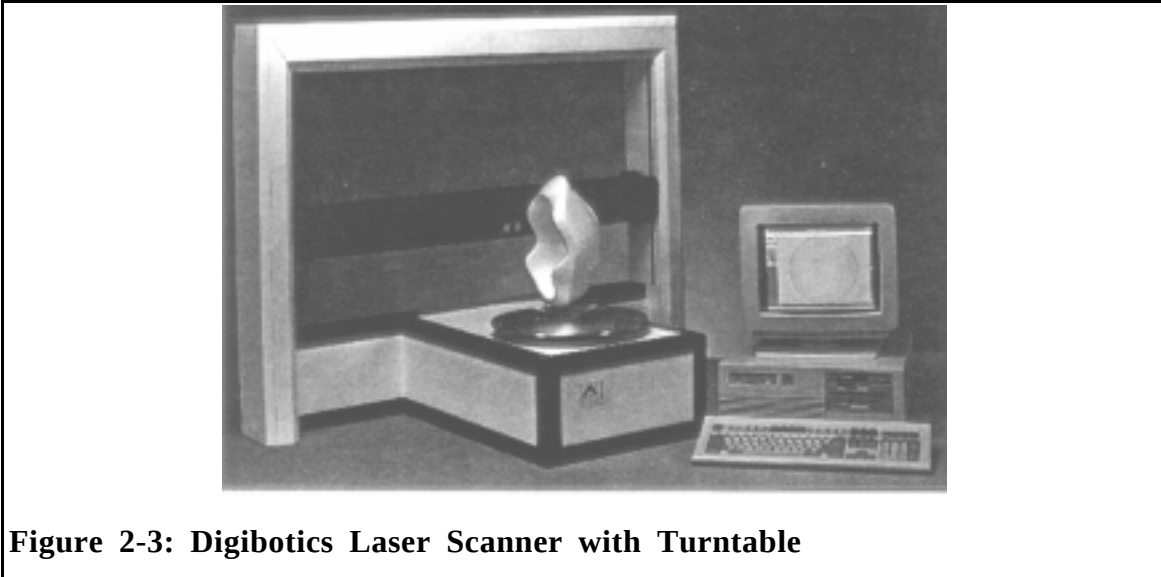


Figure 2-3: Digibotics Laser Scanner with Turntable

Other methods of gathering a point cloud are CT scanning and physical slicing and scanning such as in the digital human project. Industrial CT scanning is being developed by General Electric with claimed accuracy results of .001 inches. But, the cost of the machine and operation is still extremely high which makes it impractical for use in this research. Physical slicing and scanning embeds the object in a material which provides optical contrast to the part material. A thin layer of the object and embedding material is milled off and the surface is scanned. This obtains the geometry of the part in a discrete layer by layer fashion. This method is patented by a group in Israel [Ben Ezra] and a company named Capture Geometry Inside (CGI) is beginning to market its own version of physical slicing and scanning. Sample output from the CGI scanner is seen in Figure 2-4. Notice how this method has the ability to register the surface point information on the inside of the part. There is also a group in Japan which has developed a microslicing technique for creating 3D images of small items such as insects [Kobayashi]. Both CT scanning and physical slicing and scanning are the only methods which have this ability. All other methods only capture exterior surface information. But, obtaining internal surface information is important to this research. Physical slicing and scanning is the method used in this research and is fully described in the Reverse Engineering chapter found on page 47.

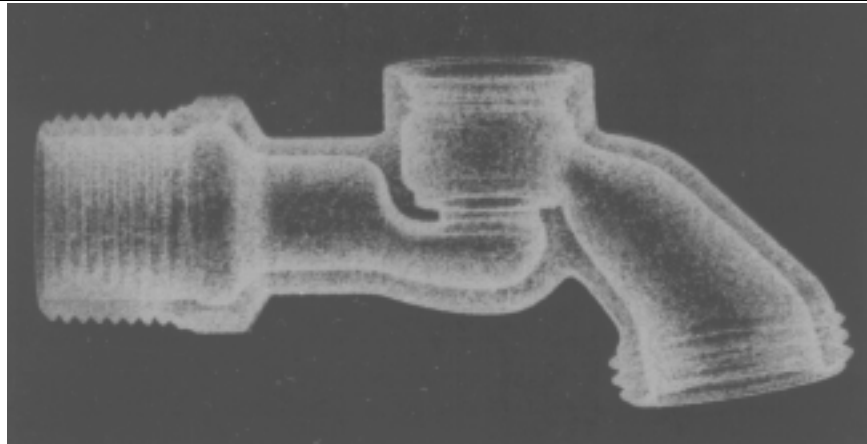


Figure 2-4: CGI Point Cloud Results of a Faucet with Internal Geometry

Surface data points alone have little design utility. Surface point information gathered along parallel lines from any digitizing method can generate CNC toolpath information. CNC code, however, is a difficult if not a useless medium for design. Small changes to the programming code are difficult and major changes are impossible. If the object geometry is C1 continuous and somewhat simple then it is also possible to fit splines to the scan lines. But, this imposes severe limitations to the complexity of the part.

Data gathered from non-contact CMMs often contain a great deal of noise. This noise must be manually removed or filtered. Awkward surface topology must also be manually handled. In order to deal with the difficulty of 3D point cloud data, 3D surfacing software has been developed by several companies. Imageware's Surfacr, Parametric's Pro/Scan-Tools, Cyberware's Cyserf are three commercially available software products. Like the rapid prototyping industry, these tools are still in evolution. They can still only produce limited computer models. For example, holes and sharp corners are still impossible or at least very non-intuitive to create in the current commercial software.

Research in reverse engineering continues to progress. In 1994, a mathematical and computational method for generation of a polygonal surface model (similar to .STL format) from raw data points was created by a group at the University of Washington [Hoppe]. In order to complete our design cycle, this method was used to create our electronic models. Another method developing at the University of Utah [Thompson] allows the user to interact with the points and define the geometry using shape features.

2.1.4 Editing CAD Model

There are a great number of computer aided design programs for electronic models. Describing each of them would be futile, but all of them run on a main theme which can be explained easily by describing the most popular ones.

Currently, the most popular computer aided design program in the market place today is AutoCAD. Its basic function is as a drafting aid. Recently, it ventured into the design of 3D surface models. Methods for taking 2D drawings and converting into 3D have been mathematically proven and demonstrated in software [Markowski and Wesley], [Gossard and Sakurai]. There are some limitations to the types of 2D drawings that can be used but nonetheless within those limitations a complete 3D description of the model can automatically be generated. In AutoCAD, however, these methods are not currently being employed and the user must laboriously describe the 3D object using projections from the 2D object. AutoCAD does have the capability of creating 3D surfaces and then finding intersections of all the surfaces in the model to define the object.

Rather than surface modeling, solid modeling is becoming more popular among the 3D CAD modeling programs. The most popular of these packages is Pro/Engineer developed by Parametric Technologies in Waltham, MA.

In this research, a polygonal solid model is used which utilizes a winged edge representation to form the solid model. Polygonal solid models do not have the exactness of a solid modeler like Pro/E but for the purpose of this research it is adequate. Commercial software such as FormZ uses this type of polygonal solid model and is commonly called Boundary Representation or BRep.

While not implemented in this research and only beginning to be commercially available, it has the ability to design using “shape features”, e.g. stock, pocket, through hole, etc. Such “shape feature” are higher-level descriptors of the CAD model. They can play an important role in efficient shape editing during CAD model creation and modification. They can also play an important role in down-stream manufacturing applications that use the CAD model. Rather than just the raw geometry, the CAD model knows how it is put together. It is a model closer to how the designer actually perceives the model. These tools are talked about further in chapter 8 on page 93.

2.2 Results of Research

This thesis describes the realization of a rudimentary design cycle. It contains all the necessary components to continually interchange physical and electronic models. Several parts of the existing design cycle which involve the translation from one medium to the next are still manual, meaning that there is a great deal of human interaction. However, many of the actions done by the user right now in theory can be automated. High level decisions will always need to be made by the user, but much care has been taken to insure that mundane tasks can be automated.

In each step of the Design Cycle, a block with a cut and a hole (Figure 2-5) is used as the test piece. Even though it is a simple shape, it is helpful in demonstrating some of the problems encountered and solved in this research.

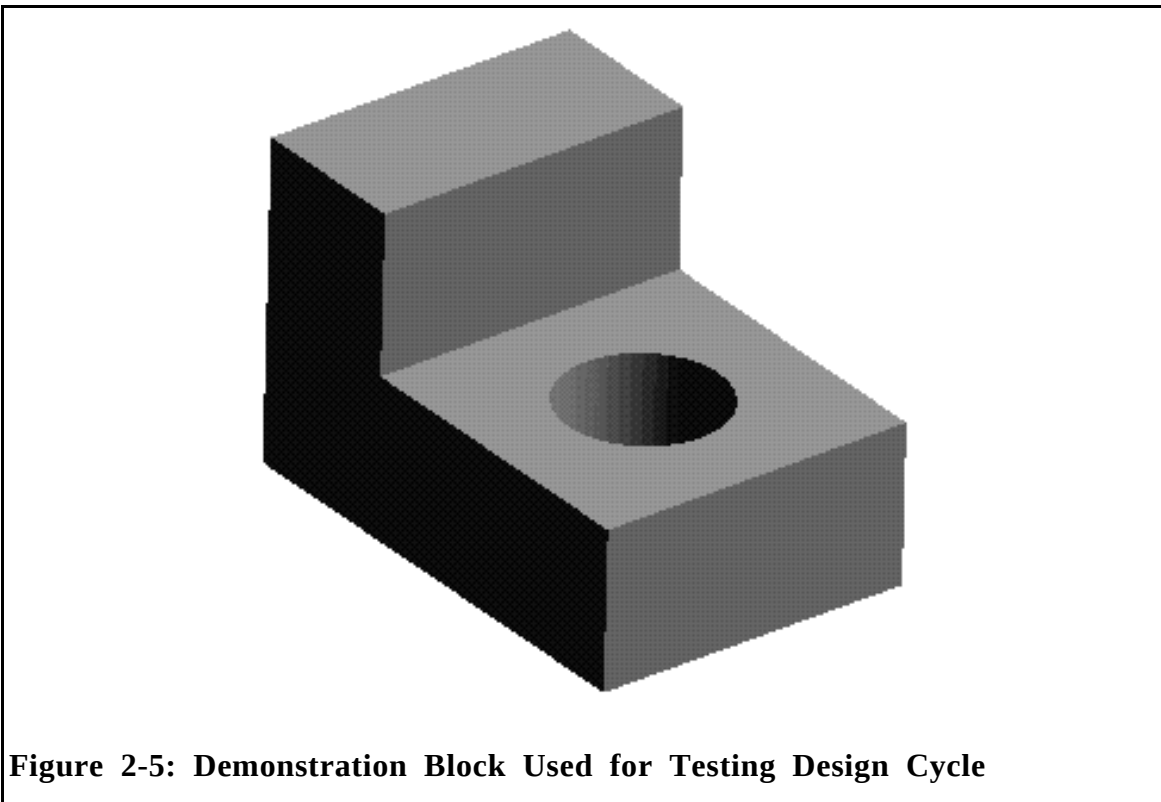


Figure 2-5: Demonstration Block Used for Testing Design Cycle

The applications chapter on page 81 explains some instances of how the design cycle can be applied. In particular, the design of a complex sculptured razor handle (Figure 2-6) is completely demonstrated.



Figure 2-6: Complex Sculptured Razor Handle

The existing design cycle is not a perfect system yet it is complete. A few parts of the system are very user friendly but unfortunately others are not. Nevertheless, the design cycle is now in a state where it can be explored and optimized. Better tools can be found or developed and the time required to translate between modeling mediums can be reduced. The recommended direction for the future work of the project is found in the last chapter on page 93.

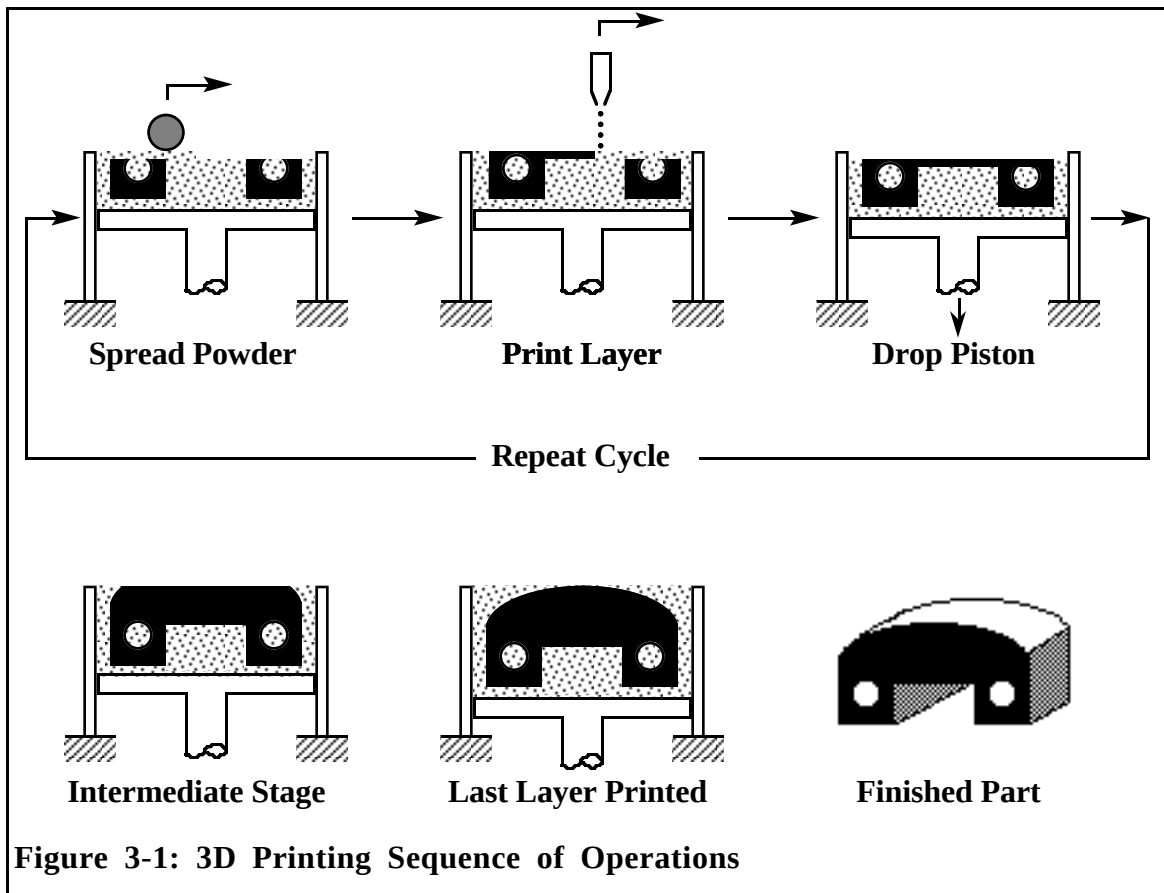
3. Rapid Prototyping

3.1 Method

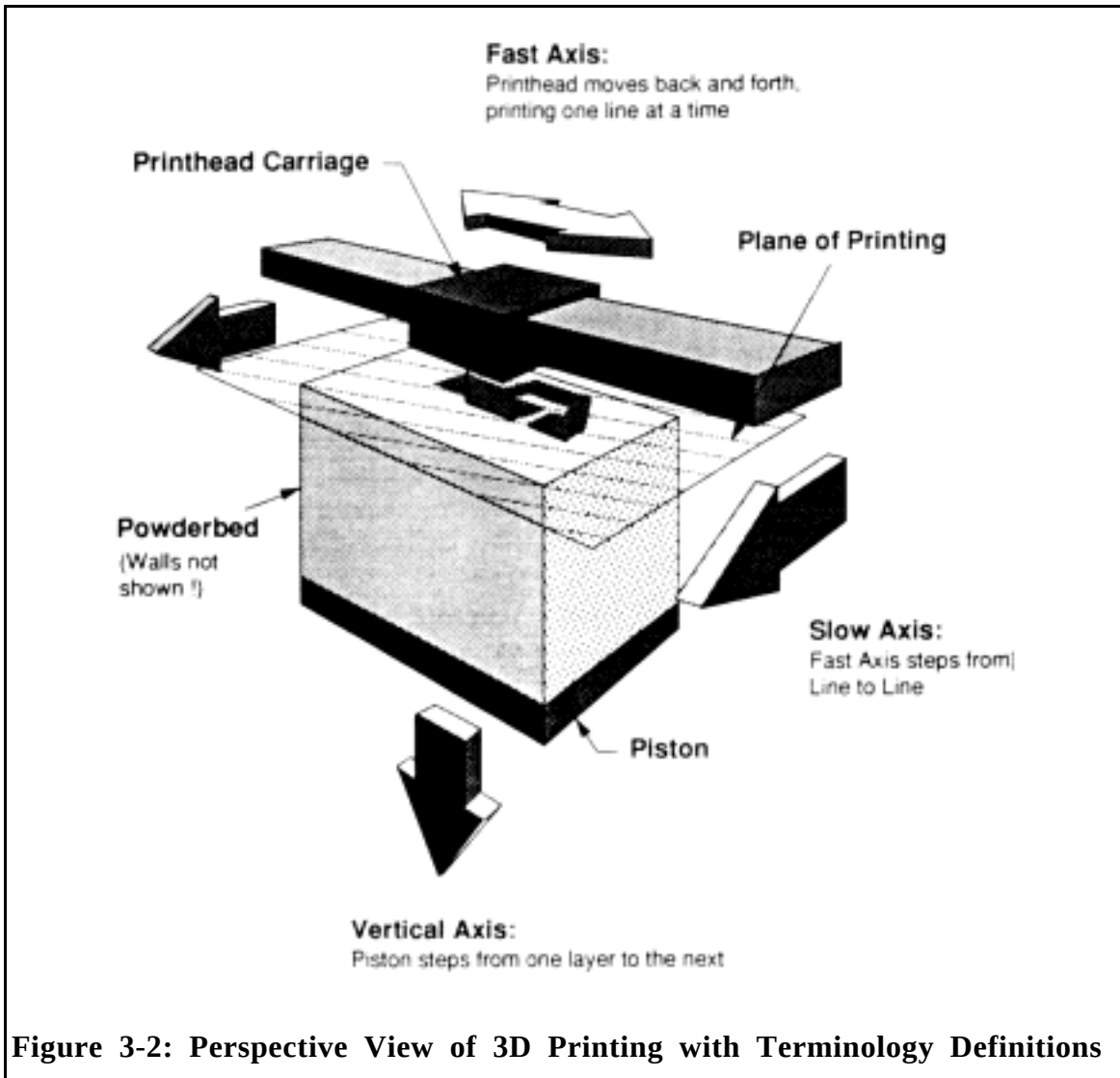
As mentioned in the previous chapter, currently there exist several methods for rapid prototyping. Each of these techniques are improving at a rapid pace. Research results in dimensional accuracy, surface finish, structural integrity, and build speed are all evolving to a higher level of proficiency. For this work, however, the method used is not a critical issue. Any method with the proper qualifications for material properties (page 34) will serve the purpose. Therefore, in order to proceed with the research, this work utilizes a manufacturing technique called Three Dimensional Printing (3DP) which was invented and developed at MIT [Sachs].

3.1.1 Three Dimensional Printing

Like the other methods described in chapter 2, Three Dimensional Printing creates parts by a layered manufacturing process. The information in each layer is obtained by applying a slicing algorithm to the computer model of the part. An individual two-dimensional layer is created by adding a layer of powder to the top of a piston and cylinder containing a powder bed and the part being fabricated. The new powder layer is selectively joined where the part is to be formed by “ink-jet” printing a binder material. The piston, powder bed and part are lowered and a new layer of powder is spread out and selectively joined. The layering process is repeated until the part is completely printed. The unbound powder is removed, leaving the fabricated part. The sequence of operation for 3D Printing is demonstrated in Figure 3-1. A perspective view of the various 3D Printing terminology is shown in Figure 3-2.



3D Printing is one of the most flexible of all the rapid prototyping techniques. The process can create parts of any geometry. The support gained from the powder bed means that overhangs, undercuts and internal cavities can be created. A ceramic filter created by 3D Printing that has internal cavities is shown in Figure 3-3. Other processes need to build support structures along with the part to create these difficult geometries. Upon completion, these support structures must be removed and leave a rough surface where they were attached. 3D Printing also has material flexibility because it can form any material which can be obtained as a powder - which is about any material.



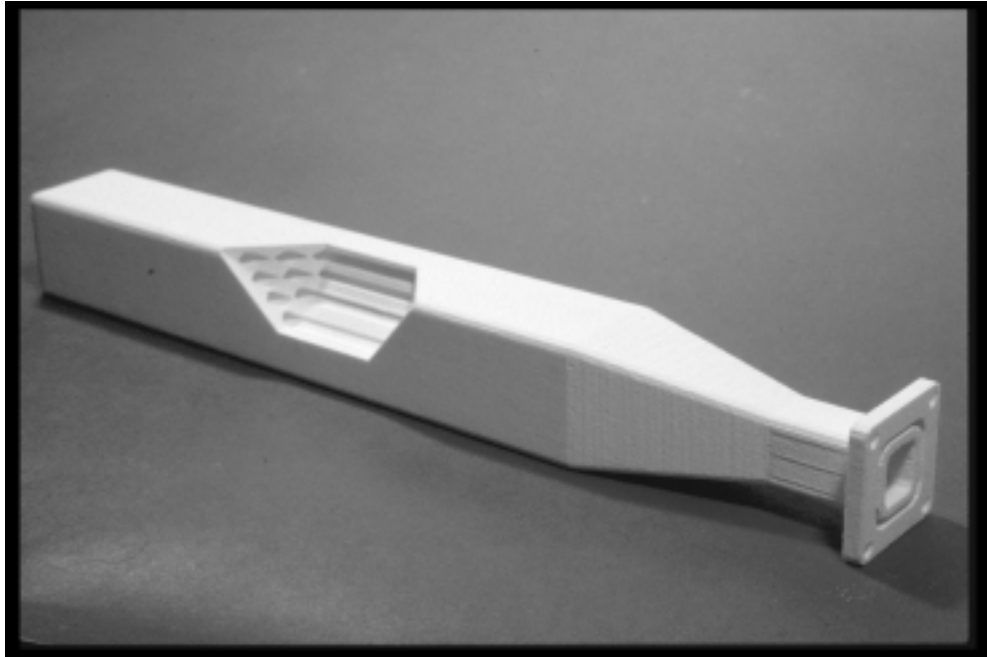


Figure 3-3: Filter Created by 3D Printing – Demonstrates Internal Geometry Capabilities

3.2 Prototyping Material

Industrial designers use materials like bass wood, clay, RenShape, and polyurethane dense foam. While these materials are incapable of being 3D printed, properties are taken from each of these are mixed to create the requirements for the design cycle prototyping material.

3.2.1 Requirements

The requirements for the prototyping material are as follows.

- The material must be printable by currently available 3D printing processes. This allows the user to build any possible complex geometry.
- Must be able to carve, sand, machine, join, manipulate by hand, and paint the material. These are properties taken from the different currently available prototyping materials.
- Must be inexpensive. Since the model may be built several times, it is important to keep the costs to a minimum.
- Higher melting temperature and high visible contrast from embedding material (see p.47)

3.2.2 Trial Materials

Three Dimensional Printing has been used to create parts out of several materials, including ceramics, metals, polymers, and glass. With the exception of glass, these materials by themselves are unsuitable as a modeling medium primarily because of the second and third requirements. But, using various waxes as infiltrants (3.3 Infiltration p.37), three of the materials, ceramics, metals, and glass, exhibit characteristics of suitable modeling materials.

The different infiltrant waxes used in experimentation are: paraffin, bees wax, candelilla wax, carunaba wax, Tektronix color wax (see 3.5 Initial Wax Printhead Results p.40), investment casting blue wax, and machinists wax. The waxes are listed in ascending order of melting temperature from 50 to 120 degrees Celsius. Each wax has a different melting temperature, color, and hardness. While there are many factors in the final properties of the prototyping material, the waxes play the most significant roll in determining the handling characteristics.

3.2.3 Experimentation and Analysis of Prototyping Materials

Over twenty-five different combinations of wax and powder were experimented with to find the ideal prototyping material. Not all of them will be explained. Some of the other variables for the combinations were powder size and powder geometry.

3.2.3.1 Alumina

Combinations of alumina and wax were the first materials tried. Alumina is a ceramic, is white in color, and comes in different particle shapes. The two geometries tested were platelet and spherical. Alumina is printed using silica as a binder and the binder is burned out to create a self-supporting part.

The two particle shapes of alumina powder were tested in combination with all eight waxes. The candelilla and carunaba wax proved difficult to work with after hardening because they are both so brittle. Cracks would develop and small pieces would chip off. The same holds true powders combined with these waxes. A much softer wax is needed for this modeling material.

While alumina may actually be a fine material for printing and display, it is not a good material to work with using hand or machine tools. The ceramic is too abrasive for hand and machine tools. Working the material with a razor blade, scraping against the ceramic, leaves black streaks that are actually residue from the metal blade. Since the reverse

engineering process uses milling, the ceramic might ruin the cutting tool and make the imaging difficult.

3.2.3.2 Stainless Steel

Stainless steel was not thought to be a very good modeling material, but was tried because it could be 3D printed. To add breadth to the material experiment several waxes were infiltrated in small printed blocks of powder. All eight waxes mentioned above were infiltrated into stainless steel powder. The paraffin, bees wax, and, if careful, the candelilla could be infiltrated directly into a printed part. The rest of the waxes have a high melting temperature which breaks down the acrysol used for binding the metal powder during printing. During infiltration the parts sag and slowly disintegrate.

In order to get the parts to hold together during infiltration, the stainless parts can be sintered slightly so they could have strength beyond that of just the acrylic binder. By using sintered parts, however, the parts developed strength beyond that desired for a modeling material. From a subjective point of view, none of the combinations “felt right.” Therefore, stainless steel was eliminated as a possible candidate for the prototyping material.

3.2.3.3 Glass

Three different sizes of spherical glass powders were experimented with: 39–45 micron, 55–69 micron, and 75–90 micron. Each of these were infiltrated with wax. As with the stainless steel powder, only the lower melting temperature waxes could be infiltrated into printed parts. The higher melting temperature waxes broke down the acrysol binder and disintegrated the part. Glasses can also be sintered to give them strength but once again the parts then have too much strength and are no longer viable modeling materials.

After infiltration, each of the three sized powders behaved identically. The speed of infiltration is however dramatically different. The smaller powder infiltrates much slower than the larger one. This is important because even at the low melting temperature of bees wax, the acrysol begins to break down after prolonged elevated temperature. In a test using an eighth inch square rod two inches long, a rod with larger powder is infiltrated by immersion into the molten wax on the order of seconds whereas the smallest powder is infiltrated on the order of minutes.

Another major drawback to the smallest of the glass powders is its inability to be spread easily in the 3D printing machine. It clumps and drags and make a mess of the printed layer. On the other hand, the largest powder spreads and prints beautifully.

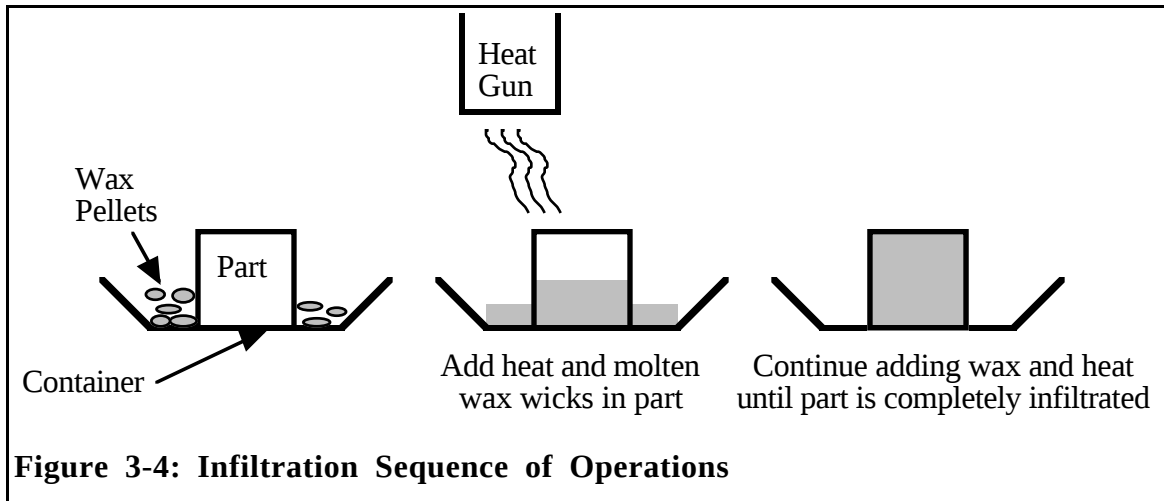
Out of all the materials tested, spherical glass powder 55–69 micron beads with bees wax infiltrant proves to be the most ideal modeling material for the design cycle. It fits all the outlined requirements described in section 3.2.1. It can be 3D printed using acrysol (an acrylic binder). It is also very inexpensive: < \$1/kg. The only drawback to this material system is that the melting temperature of the wax is quite low which limits the materials available later as embedding material.

3.3 Infiltration

Infiltration is not an important step in the final idea of the design cycle if a wax printer is eventually realized. It is only an intermediate step allowing the progression of the research. But, because it proved a hurdle in this research the method for infiltration needs mentioning.

First attempts to infiltrate parts were done by dipping the parts in a bath of molten wax. While this may seem a simple task, several problems arise with this method. The major problem comes in retrieving the part from the wax. The melting temperature of the wax is about that of the break down temperature of the acrysol which is holding the part together temporarily. If the wax temperature is not carefully monitored, the part may slump or deteriorate completely in the molten wax. Also, even by monitoring the temperature and keeping well within a tolerable range, retrieving the part becomes difficult because it is soft to the touch and will deform under any gripping pressure applied to retrieve it. Many parts were destroyed simply by touching them and others collapsed under their own weight.

Infiltration can be successfully accomplished by incrementally melting small amounts of wax and letting that wax wick in the part. This allows a great amount of control in the infiltration process. The part is never touched during the entire process and the part maintains its shape perfectly.



The one draw back to this method of infiltration is that since there is so much control over the rate and temperature of the wax and part, the acrysol does not burn out. This yields a final part that is somewhat stronger and less malleable than that done by the simple dipping method. However, this is only a problem for a designer who wants to be able to use their fingertips as shaping tools because it becomes more difficult to do so.

3.4 Examples

The following are examples of different parts printed with the medium sized glass powder and then infiltrated with white bees wax. Figure 3-5 is a simple block. This block is used as the standard part in all of the testing for both rapid prototyping and reverse engineering and will show up again and again. Its dimensions are approximately 0.75 inches long and 0.5 inches wide and tall.

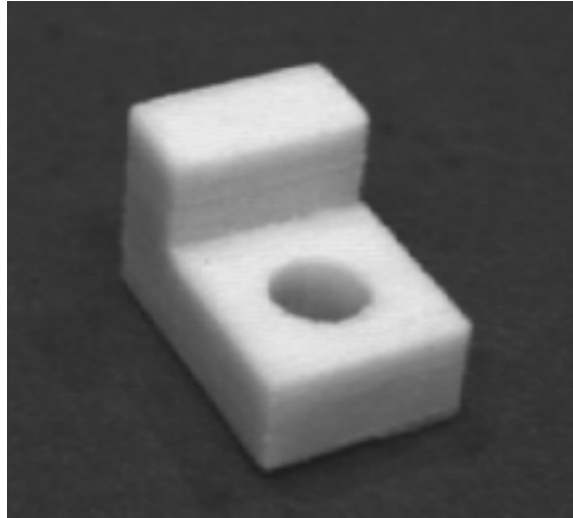


Figure 3-5: Glass Powder Block Made by 3D Printing with Bees Wax Infiltrant

Figure 3-6 comes from a file created by the Architecture department at MIT. It clearly demonstrates the fine delicate features that are manufacturable by 3D printing without the necessity of support structures for the arms. The parts have a span of just over one inch.

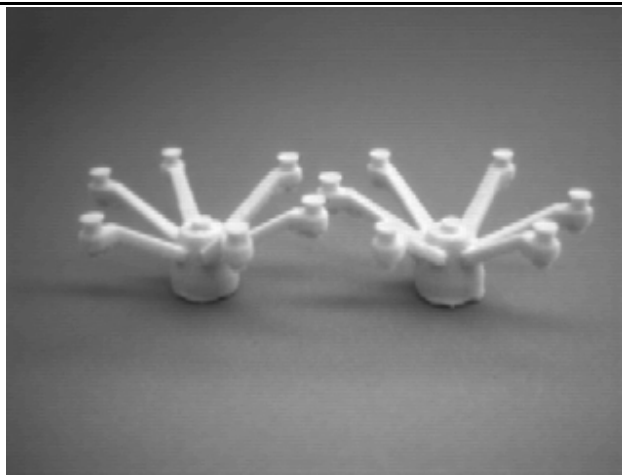


Figure 3-6: Glass Powder Objects Made by 3D Printing with Delicate Arm Features

3.5 Initial Wax Printhead Results

A student working in the 3DP lab did work on implementing a “drop on demand” printhead useful for 3D Printing [Becher]. He used a commercial dye sublimation wax printhead from Tektronix and printed into stainless steel powder. His initial results were quite promising. As follow up to his work, experiment were performed with his apparatus using the Tektronix black wax and spherical glass powder in a temporary powder bed. The black printed line can be seen in Figure 3-7. The individual glass beads can be seen more clearly in Figure 3-8. These lines also show the uniform, cylindrical nature of wax printing into the glass beads.

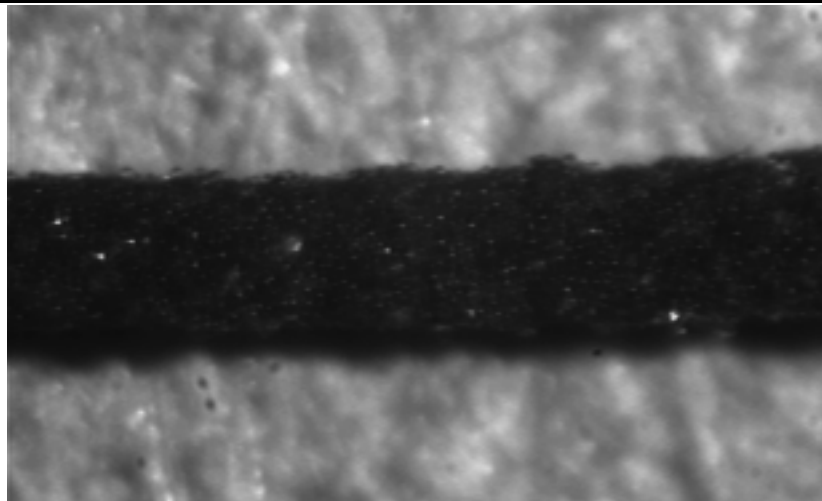


Figure 3-7: Printed Line of Black Wax and Spherical Glass Powder

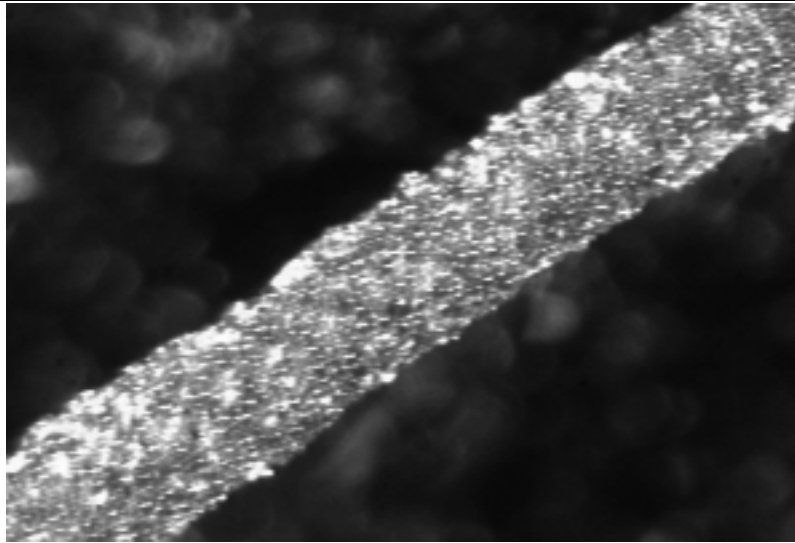


Figure 3-8: Printed Wax Line

The lines are quite strong. They are self-supporting and can be easily manipulated by hand or tweezers with no deformation. Figure 3-9 is a cut cross-section of a similarly printed line to those just pictured in Figure 3-7 and Figure 3-8. Clearly again the line is cylindrical and the wax has penetrated completely through to the core.

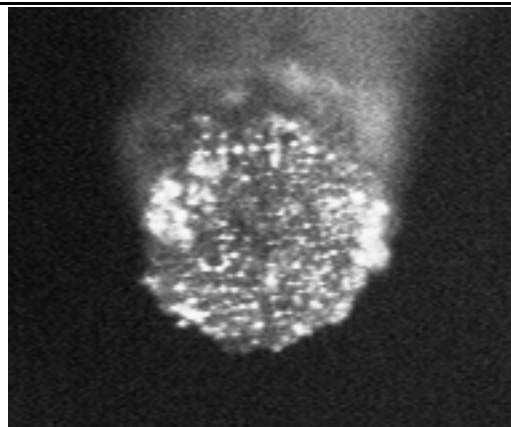


Figure 3-9: Printed Wax Line Cross-Section

The printhead setup is unable to create parts of any geometry other than lines. It only allows for the printhead to travel linearly and to be on or off. To see the effect of printing one line on top of another to simulate the real 3D printing process several lines are printed

parallel to each other. By adding powder approximately 5 mils thick and rotating the bed 90 degrees, more lines are printed intersecting the old lines just printed.

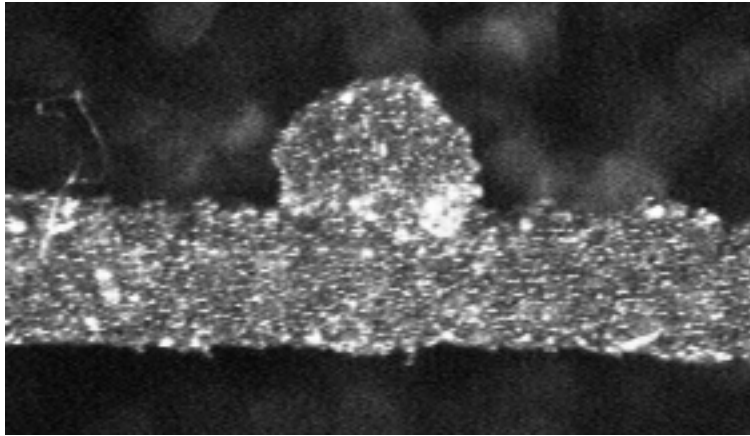


Figure 3-10: Printed Line with Cross Part

The results in Figure 3-10 show a new line right on top of the old and perfectly bonded together. The printed part actually formed a cross but in order to image the results the excess portion of the line was removed. These results are encouraging. Further examples of how the wax printhead could be used are explained in chapter 8 on page 93.

Chapter 4

4. Edit Physical Model

4.1 Material Qualities

In chapter 3, the properties for the prototyping material are outlined. One requirement of the material is that it can be manipulated by carving, sanding, machining, and joining. Each of these requirements have been met.

4.1.1 Carving

Carving is the easiest requirement to satisfy. Most materials can be cut and carved. This prototyping material needs to yield to simple hand carving pressures. The material behaves much like hard soap when carving; although, it does not begin to melt in your hand like soap. Deep cuts remove shavings such as those you would see when carving wood while light cuts with a blade remove only small amounts.

Since most of the structural strength of the material comes from the wax, no appreciable damage is done to the blade during carving. This is significant because glass is abrasive and if there were glass bonds between individual powder elements then most tools would wear out quickly.

4.1.2 Sanding

Sanding is much like sanding wood. The feel is exactly the same. There is a perceived difference in the way the material actually comes off. Since the designer is sanding wax, wax gets in the sandpaper and a thin film of wax about as deep as the grit of the sand paper permanently stays there. Nevertheless, the function of the sandpaper has not altered. Vigorous sanding is not recommended. If a great deal of material needs to be removed, then carving should be employed and sand only as a finishing touch.

Since the material is malleable with hand pressure, finish sanding can often be accomplished simply by rubbing finger tips over an area. This actually gives a better finish than using sand paper.

4.1.3 Joining

There are two different types of joining. They differ in the amount of material being added to the existing object. Small amounts can be added to an object to help cover up imperfections such as in finish sanding or filling in nicks and holes. This can be accomplished simply by taking shavings of the material and working them into the part by hand. The added material quickly joins the object and disappears like lotion on dry skin by simply rubbing gently using fingertips.

The fact that material can be added simply and easily is a very powerful tool and major improvement over existing practice and therefore needs special mention. In order to add small amounts of material to wood, RenShape, or dense foam, a designer uses a compound called Bondo. It is a sticky paste which hardens after the addition of a catalyst. It is messy and difficult to work with. In an iterative process where a designer would try to find just the right shape by adding and subtracting material over and over again, Bondo is a terrible material but is still the premiere in model shops. The bees wax and glass compound make the iterative process of adding and subtracting easy.

The other type of joining is major pieces being “glued” together. Because of the wax, the material has some tackiness. Simply by pressing two pieces together they will stay, but their bond is very weak. In order to make a much better bond, a heat gun directed toward the area of contact melts the wax slightly and makes for a perfect glue. The bond is just as good as anywhere else in the part. To hide the joint, simply do as mentioned above and rub in a small amount of material and the joint will become perfect visually as well as structurally.

4.1.4 Machining

Sometimes major work needs to be done to an object. Most operations that can be done with a machine tool such as a Boolean operation can probably better be done in the computer environment rather than on the physical object. Nevertheless, if it necessary the prototyping material can also be machined.

The material has internal strength to handle machining operations. If something did go wrong and the part cracked or broke, it could always be “glued” back together with no harm as described in the previous section.

4.2 Survey

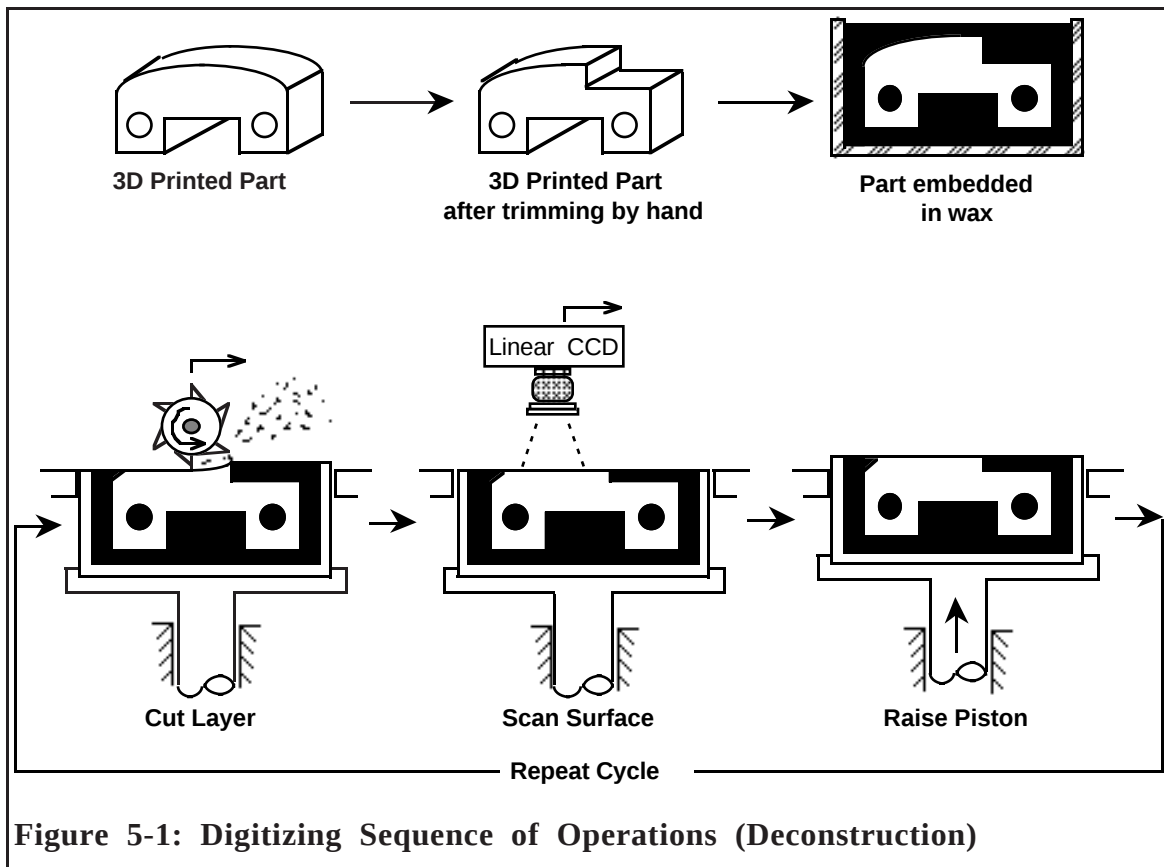
A formal controlled survey of practicing model makers over a substantial time period would have been a nice addition to this thesis. Unfortunately, this was not done. However, in an informal, non controlled survey of people who had done some modeling of objects before, the material described in this thesis had a favorable first impression. Initial reactions were typically skeptical. After describing and demonstrating some of the characteristics of the material, however, opinions changed and continued to improve as the person being surveyed worked with the material.

Chapter 5

5. Reverse Engineering

5.1 Method

After the designer is satisfied with the changes to the physical model, the part must be reverse engineered. This requires digitization and is accomplished by decomposing the part layer-by-layer; basically the reverse of how it was created in the first place. Figure 5-1 demonstrates this process.



First, the physical model is embedded in a block of material which acts as a physical support and provides optical contrast to the model. A layer of this block of material is shaved off using a simple form of milling. After each layer is removed, an optical scanner captures an image of that layer, based on the optical contrast between the part and the support material. Milling and scanning are repeated until the entire part is imaged.

This approach has several key benefits. First, since the part is decomposed on a layer-by-layer basis and since it is held in place by a support material, any geometry can be imaged. The full set of data is obtained from one “set-up” with no need to fuse the data from multiple views. Further, the data is delivered in a Cartesian coordinate system, permitting easy analysis.

The single disadvantage of this approach is that it is destructive. However, the model is only digitized after all modifications have been made. Since the next stage involves working with the electronic model, there is no need for the physical model after it is digitized. Should a need arise, a new model can always be printed from the electronic model.

5.2 Embedding Material

Finding the right embedding material is a balancing act between its properties and that of the prototyping material. Here two materials are chosen which best fit the required properties. One system is used in the current research and another is recommended as the material for future continuation of the research.

5.2.1 Requirements

The following are the required characteristics of the embedding material.

- Lower melting temperature than the prototyping material. This helps the object maintain its geometry during embedding.
- Does not crack during milling. Cracks and chips show up in the scans as lines and speckles and are difficult to filter out digitally.
- Small change in specific volume from liquid to solid. This insures that the embedding material completely encases the object and does not leave holes or depressions.
- Low viscosity so that it will fill all cavities.

- High visual contrast from prototyping material for better clarity in scanning.
- Opaque so that embedded features remain hidden until cut.
- Fast solidification time.
- Inexpensive.

Many of these characteristics were defined before work began and a few such as the cracking became important only after experimentation.

5.2.2 Experimentation and Analysis

Ten material combinations ranging from waxes to polyester resins and epoxy were tried with varying levels of success. Each is described below.

5.2.2.1 Epoxy and Resin

Clear Epoxy – Obviously epoxy violates some of the most important required material properties and can not be used as an embedding material but it does reveal some important factors. First of all, epoxy at room temperature is viscous and traps many bubbles in the embedding. It also takes a long time (~24 hr.) to solidify. Both of these negative properties can be improved dramatically by raising its temperature since epoxy solidifies in an exothermic reaction. A few degrees is all that is necessary. Still the most glaring problem with clear epoxy is that it is translucent. A scanning device can see a complete silhouette of the entire embedded part and not just the cut surface. With careful digital filtering, the part outline on the cut surface can be found roughly but it is not a good image.

Black Epoxy – I will lump black epoxy and epoxy with a carbon black dispersion in the same category because they had similar results. There are many applications which use black epoxy such as encasing the components of a circuit board for protection. As described above in the clear epoxy section, the viscosity and solidification time can be significantly lowered by slightly raising the epoxy temperature. Also, with the black dispersion, it becomes opaque and should be a good contrast to the part. Unfortunately, when the epoxy is milled, instead of the expected deep dark black, the surface is locally very rough and scatters light yielding a light gray finish.

Polyester Casting Resin with Black Die – This is the other experimental non-wax material. The resin has similar properties to epoxy and reacts the same to temperature. The black die

provided by the manufacturer creates a slightly translucent black finished product. Unfortunately, the curing time still took many hours even at elevated temperature.

5.2.2.2 Wax

A host of waxes were tried because of their quick solidification time and also because they are non-caustic.

Candelilla and Carunaba – These are waxes that can be used only with higher melting temperature prototyping materials. Even then they are not good because they are both still quite viscous in their molten state. Also, they are both very brittle. They chip and crack easily during milling therefore are not good embedding materials.

Bees Wax with Carbon Black Dispersion – This wax has most required properties except when it is solidified. Beeswax is a very ductile and tacky material. While that may be good for a prototyping material it is poor as an embedding material because it gums up the cutting tools.

Black Wax Paint – This is a purified beeswax with a black resin and well qualifies for the opaque and high contrast material properties. But, because it is sold as a paint, it is unfortunately quite expensive. Even though it is more suitable as an embedding material than regular bees wax, the expense eliminates it.

Tektronix Black Wax – This is another suitable material but because it is a proprietary peripheral to a commercial product, the expense makes it impossible to use. (The reason that it could be used as part of the prototyping material is that it is simply a binder and not a major portion of the object volume.)

Machinable Wax – This is a prototyping wax used for machining. It is designed to be machined and would be perfect in that respect. However, its melting temperature is significantly higher than all other waxes mentioned. Furthermore, in its molten state, it is very viscous making it unsuitable.

Investment Casting Wax – This wax in its natural state is blue. It can be used either in its natural color or with a carbon black dispersion as described in the Two or Three Colors section of digital registration (section 5.5.2.2 p. 55). This is the only wax with small change in specific volume from liquid to solid. It also is not viscous in the molten state. Its

one drawback is that its melting temperature is higher than that of the chosen prototyping material's.

Paraffin with Carbon Black – Paraffin has a viscosity near that of water and has the lowest melting temperature of all the waxes. The carbon black gives it good contrast with the part. It also solidifies within minutes after pouring. The one drawback is that its specific volume change between liquid and solid state is very high. Paraffin is used for candle making and as the candle is cooling, the candelmaker must refill the mold 3-4 times to replace the loss in material volume.

5.2.3 Results

As mentioned at the beginning of this section, two embedding materials are recommended for use. One for use in current research and one for use in future work. The recommended embedding material for use right now is paraffin with carbon black. The exact formula for compound is 20-1-1 by weight: paraffin, carbon black, and stearine. Stearine is a common candle making additive which makes the wax slightly harder and opaque. Suggested use for the mixture is explained in the next section.

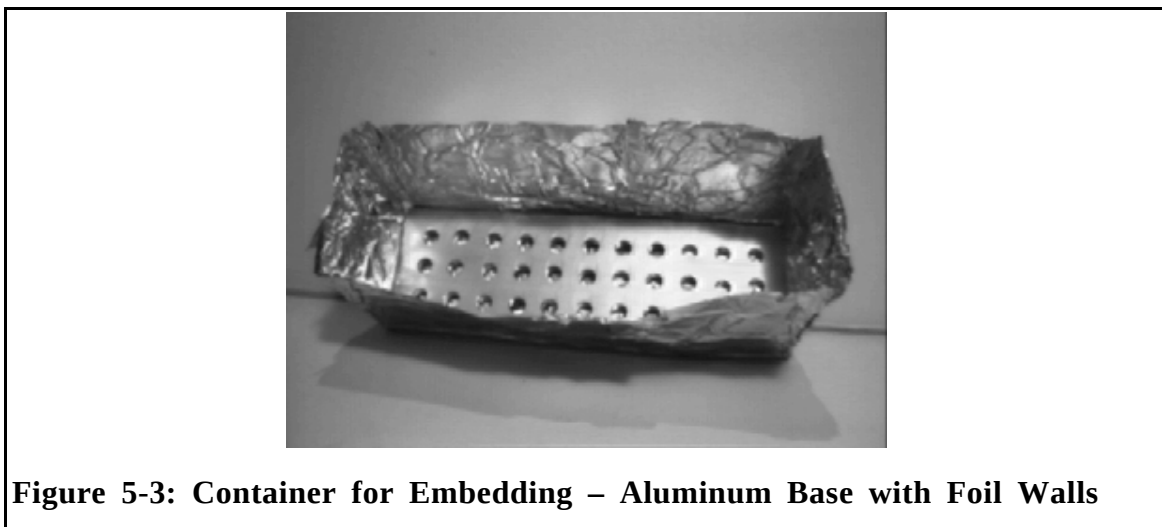
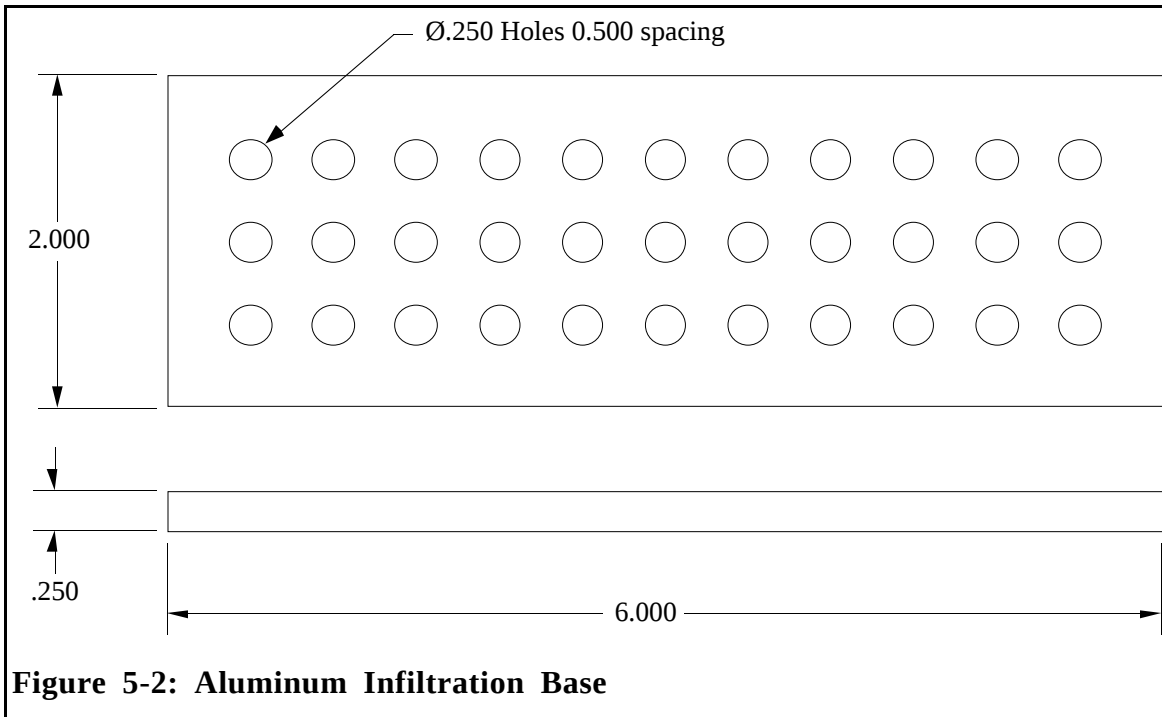
When a new 3D printing machine is created with the capabilities of printing a higher melting temperature prototyping material, then the blue investment casting wax with a carbon black dispersion is recommended as the new embedding material because it satisfies all required characteristics.

5.3 Scanning

Since a scanning machine does not currently exist, a procedure is created to mimic the functionality of a machine. Even though there are many manual steps in this procedure, most of it could conceivably be automated.

5.3.1 Setup

After a physical object is altered to a desired shape, it must first be embedded in wax. A container for the part and embedding material is created first from a base of 1/4" aluminum faced parallel on both sides with securing holes drilled every half inch shown in Figure 5-2. The walls for the container are made with aluminum foil which leaves enough room for the part and two reference marks shown in Figure 5-3.



After the container is complete then the part must be embedded in wax and reference marks must be made. The following procedure is followed for embedding the part and is shown in Figure 5-4.

1. Fill the container with wax so that all the holes are filled and the bottom is just covered.
2. Before the wax completely solidifies, add the object and make a note of how it is placed in the bed.

3. Fill the container and generously cover the part. Make sure that the new wax is in the range 65-70 degrees C. This helps insure that the wax binds with the part. Keep adding wax as depressions form.
4. After several minutes the wax will be completely solidified. Drill two 1/4" holes for reference marks. Finish the hole to just above the base with a flat end mill. **Note:** Do not drill through the part.
5. Fill the holes using paraffin with a white dye added. Let the wax run into the hole so that it completely fills it and does not trap air bubbles.
6. Remove the foil and clean up any wax that may have leaked through foil or under the base.

After completing the steps, the part is ready to be scanned.

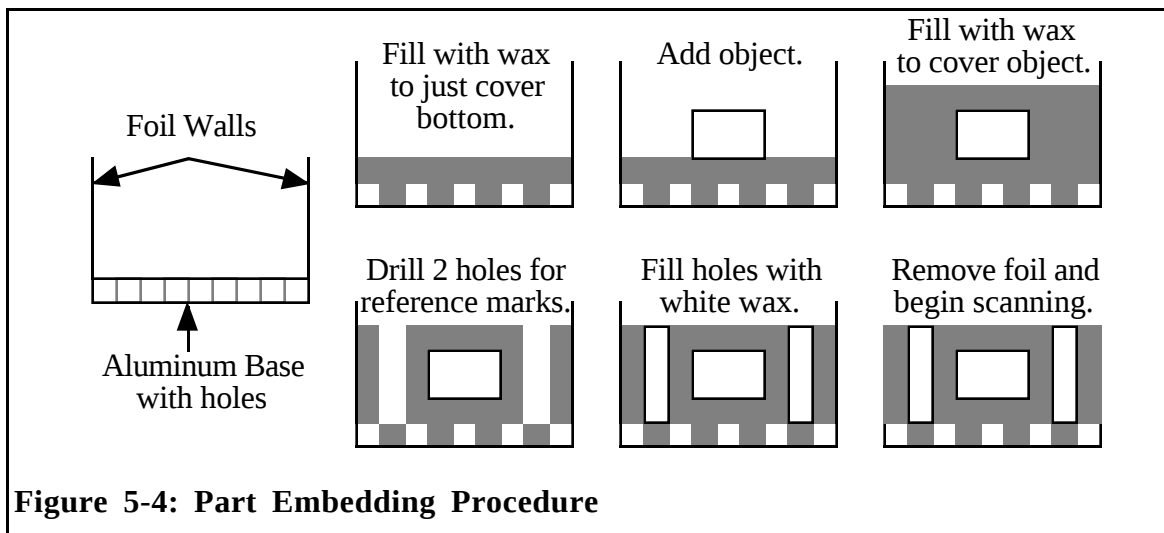


Figure 5-4: Part Embedding Procedure

5.3.2 Procedure

The scanning process is not currently automated, but it can be accomplished by hand using a milling machine with a fly cutter and a desktop scanner.

A thin layer is milled and the block of material is placed repeatedly on the same spot of the scanner using the lip of the scanner as a reference and is then imaged. This rough mechanical registration is necessary to aid in the digital registration and is explained in the Registration section on page 54. A milled layer of 0.01 inches is adequate for most parts. By initially assuring that the part begins parallel and is maintained parallel for each step, an accurate picture of each layer can be imaged. Nevertheless, errors in the same order of magnitude as the cutting thickness can occur unless great care is taken each time the part is

refixed in the mill. Therefore, cutting layers thinner than 0.01 inches is not currently recommended.

5.4 Thresholding

Each scanned image is a 256 gray level pixel map. It is important to decide what level of gray to threshold the image to distinguish the part and reference marks from the embedding material.

One method of thresholding is done using a pixel value histogram for all the images. The histogram yields two peaks, one light value for the part and reference marks and a dark value for the embedding material. A mid point between the peaks is used as the threshold value and each image is then converted to a bitmap.

Often the threshold value fell very near the midpoint of the gray level 128. Therefore, another equally valid approach to the threshold problem is to simply assume a midpoint at 128 and convert the images with that criteria. Computationally, it is significantly faster and the results are equally as good as the histogram method. Simply for time's sake, the assumed midpoint method is recommended. However, in future applications where the problem may not be as simple as separating black and white, the histogram method would probably yield the best results.

5.5 Registration

One of the major benefits of the previously described digitizing method is that very fine details of the original object can be captured. While each layer can reveal very fine features, if they are not stitched together into a global picture then much of this scanning method's desirable characteristics are lost. Furthermore, the part is destroyed with no possibility of regenerating it again. Registration is a technique implemented to maintain layer by layer information.

5.5.1 Mechanical

Mechanical registration involves creating an encasement for the part which has three orthogonal surfaces. The base of the block is used to keep the part parallel with the cutting plane. Thus the top and bottom are always parallel. There must also be two other perpendicular adjacent faces. Those two perpendicular sides are placed against the corner of the scanner creating a physical registration for the most recently exposed surface to be

scanned. Ideally this method is sufficient to register each of the cuts to the other. Unfortunately, it is very difficult to create three perfectly orthogonal faces. The two opposite parallel faces are easily created by milling with a fly cutter. The two perpendicular sides however are only possible with extremely careful milling. Even with careful milling, the more typical result are sides which are almost perpendicular thus creating a gradual slant in the scanning as that side is used for registration. Also, placement on the scanner is subject to error each time. This may cause layers to be translated or rotated by several pixels from the previous scan. A rotation of just 1 degree in placement at the top of a 5 inch part can make the bottom off by almost 0.1 inches. This is a very unacceptable error.

Through filtering (see 6.2.3 Noise Filter p.66) errors on a local level can be hidden but not completely corrected. Thus regeneration of the part can be accomplished but with noticeable error. If there is a global error such as the one of the vertical planes not being true, then there will be an obvious bias in the regeneration.

5.5.2 Digital

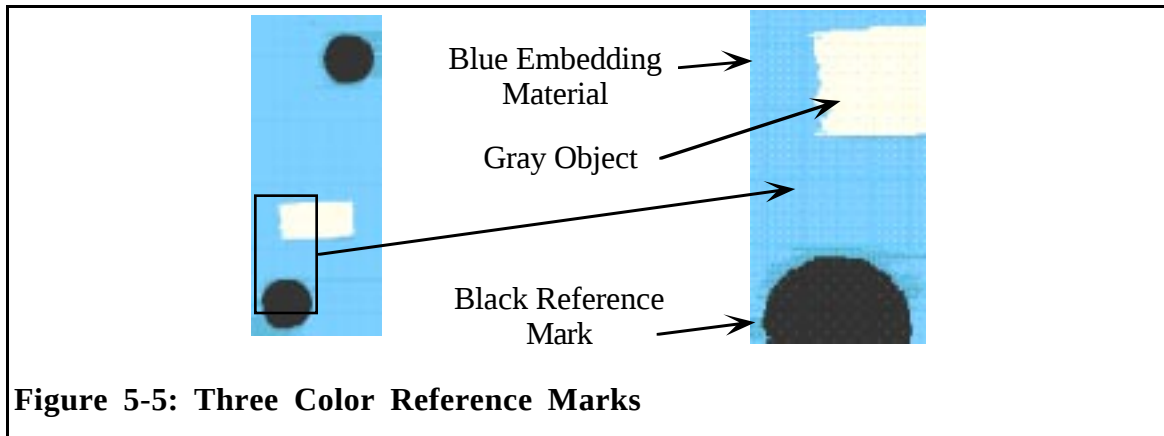
With further development work, mechanical registration may eventually yield the necessary accuracy needed for this process. However, using a digital method in conjunction with the mechanical registration allows for fine tuning the alignment of each layer. Therefore, as long as the placements of subsequent scans do not significantly change spatially, meaning more than an 1/8", then digital reconstruction is still possible.

5.5.2.1 Method

The digital method requires the placement of two registration marks perpendicular to the cutting plane. These marks are used to align the images. The challenges facing this type of alignment are fourfold. Each registration must be perfectly perpendicular to the cutting plane. The marks must be located. They must be uniform cross sections along the scanning volume and must be distinguishable from object being scanned.

5.5.2.2 Two or Three Colors

If the registration marks, embedding material, and part were each different and distinct colors or a different and distinct shade of gray then finding and separating them is an easy task. The problem lies in separating the different boundaries without any loss in border definition. If we lose the border definition then the digital alignment proves no better, in fact worse than the simple mechanical registration.

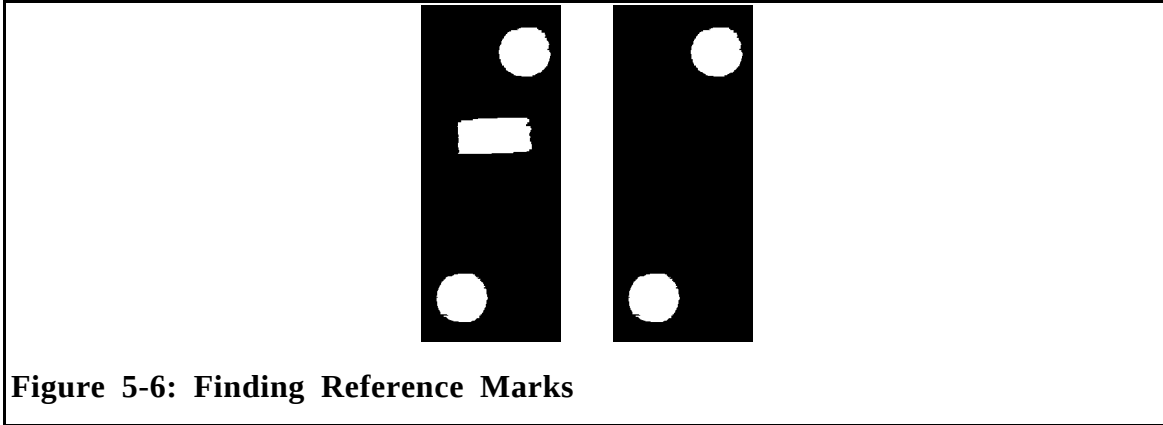


A key element to the embedding material is a high contrast from the part. This allows for clear border recognition. This property of the embedding material must be maintained. Examine a sample from a 3 color scheme. Borders of both the part and registration marks are unclear.

Recognizing that the registration marks and the part never occupy the same position in a cross section, both the part and the registration marks can be the same color which is high contrast with the embedding material. This, however, presents a new problem, namely finding the registration marks.

5.5.2.3 Search Algorithm

Since the registration marks and the part are the same color, there needs to be a method for distinguishing between them. Only the first set of reference marks need to be found because all others marks are roughly in the same location because of the mechanical registration. Fortunately, there is much information known beforehand about the locations and size of the reference marks and many search techniques could be used to find them. One technique is implemented using a genetic algorithm (GA) optimization. A GA in this case is an overkill solution for the complexity of the problem. The GA performs adequately and finds the rough center of the marks in approximately one minute and that is all that is needed here.



A very simple method that proved extremely efficient as well as effective must not be overlooked. Often a little user input can make automation much more effective. In the case of finding the registration marks, displaying the first image and asking the user to select a point inside the marks worked nicely. Finding the center of each mark only requires one seed value inside the mark. This time the human beat the machine hands down.

5.5.2.4 Finding Absolute Centers

As mentioned above, the genetic algorithm was originally implemented to find the exact center of the registration marks. However, to find the center of the marks, only one “seed” point is needed. From the seed pixel, a recursive algorithm finds the rest of the pixels in the registration marks by locating all connected white pixels. The center can now be found by a traditional center of area calculation as seen in Equation 5-1.

$$\bar{r} = \frac{\int \tilde{r} \cdot dA}{\int dA}$$

Equation 5-1: Center of Area

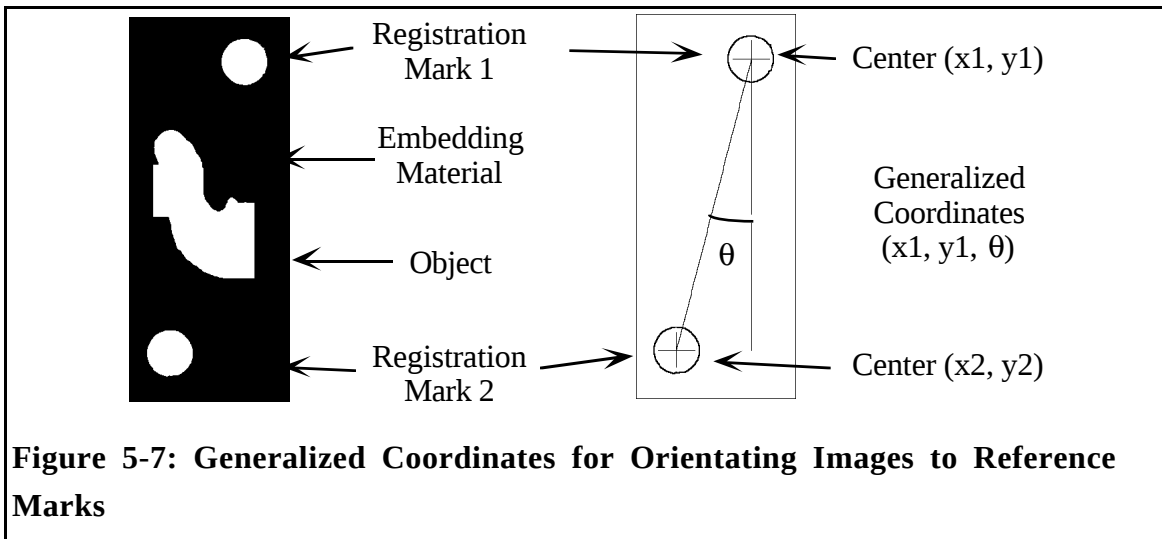
For digital images, the center of area must be calculated using a discrete form of Equation 5-1. This is seen in Equation 5-2.

$$\bar{r} = \frac{\sum \tilde{r} \cdot \Delta A}{\sum \Delta A}$$

Equation 5-2: Center of Area for Digital Shape

5.5.2.5 Alignment

Finding the centers of the reference marks is an important step. This is the beginning of aligning each of the images. With the four center coordinates alone, alignment is over constrained. This problem is similar to a classical dynamics problem of generalized coordinates for a rod in a plane. The solution for the rod problem is to have three generalized coordinates. Two of the coordinates come from one end of the rod and the other is the angle the rod makes with an arbitrarily defined fixed angle. As shown in Figure 5-7, the alignment for the images follows similarly with three generalized coordinates. Two coordinates are taken from the center of the first registration mark and the third coordinate is the angle from vertical that the two registration marks make with respect to each other.



Each image is aligned using the three generalized coordinates $(x1, y1, \theta)$. The first task is to translate each image so that the first two coordinates match. Translation is much less interesting than rotation.

In computer graphics, rotation of objects and images is usually performed by applying the rotation matrix (Equation 5-3).

$$R(\theta) = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}$$

Equation 5-3: Rotation Matrix

This works perfectly well for single points, lines, and polygons but it is inadvisable to simply apply the rotation matrix to each pixel in a bitmap image. The problem lies in that there is not always a one-to-one correspondence between pixels in the source image and pixels in the rotated destination image. Because bitmaps are discrete, sometimes in rotation two pixels will be mapped to the same location in the destination image. The rotation will map white pixels to a black destination image and because there is not a one to one mapping, the destination image will have holes. Figure 5-8 demonstrates this problem. This happens even if the source image is completely filled in. Greater rotation angles correspond to even bigger problems with a maximum 45 degrees rotation. Higher angles will have less error but this pattern will cycle every 90 degrees of rotation.



Figure 5-8: Rotation Problem – Holes in the Rotated Image

The solution to this problem is subtle. Instead of rotating and mapping each pixel into a new image, it is better to simply raster over the destination image and find which source pixel to copy by using the negative of the rotation angle. This will maintain solid white areas even without a one-to-one mapping. This is a simple point of view shift but solves the problem.

The process just described may seem like we are getting something for nothing. In actuality we are giving up one thing. If in the original image there were fine features that were only one pixel big, then they may be lost in the back rotation. However, the fine features that

would be lost using this transformation are incapable of being printed by the 3D printing process or are probably noise. Therefore, we are sacrificing noise and impossible to create geometry in order to accomplish a much cleaner rotation.

To make this process even more computationally palatable, a quick raster rotation algorithm is used [Paeth]. The essence of the algorithm comes from the observation that the rotation matrix, $R(\theta)$ can be formed by multiplying three matrices which are shown in Equation 5-4 and Equation 5-5. These are the equations used for rotation in this research.

$$R(\theta) = M1(\theta)M2(\theta)M3(\theta)$$

Equation 5-4: Rotation Matrix Simplification

$$M1(\theta) = \begin{bmatrix} 1 & -\tan\left(\frac{\theta}{2}\right) \\ 0 & 1 \end{bmatrix}; M2(\theta) = \begin{bmatrix} 1 & 0 \\ \sin(\theta) & 1 \end{bmatrix}; M3(\theta) = \begin{bmatrix} 1 & -\tan\left(\frac{\theta}{2}\right) \\ 0 & 1 \end{bmatrix}$$

Equation 5-5: Simplified Rotation Matrix Elements

While aligning the images, the registration marks are removed or blacked out because they are not needed hereafter. Upon completion, the data now represents an accurate discrete digital version of the original physical model. This model is now ready for editing.

Chapter 6

6. Editing Electronic Model

There is a fuzzy line between the transition of reverse engineering and editing the electronic model. In this thesis, a CAD model is defined as an electronic model that can be altered then exported for manufacture (in this case 3D printing).

6.1 CAD Model Representation

After the realignment of the images is complete, the data now represents an accurate discrete digital version of the original physical model. Currently, this representation, called a voxel (combination of volume and pixel) model, is receiving much attention with most of that in the medical fields as a new visualization tool for radiologists. It has also been looked at as a CAD tool for mechanical parts. In the Rapid Prototyping field, the final file format to drive the rapid prototyping machines is, in essence, a compressed voxel model of raster information. A voxel model fits the criteria for a valid CAD model and therefore must be mentioned here.

One might conclude that in this design cycle there is no need to change existing information to any other file format besides a voxel. Voxel models can easily accommodate Boolean operations, are good at file-to-file comparisons, interference checking, offsetting, and eliminate many of the problems with surface models such as overlapping surfaces. Unfortunately, voxel models require an immense amount of memory (RAM) in order to work with the model interactively. This is difficult especially if the model has very fine resolution because the file size goes up by resolution cubed. The machines needed to run such models are still expensive beyond the scope of this design cycle's target. Therefore, while in the future voxel models may become the better CAD representation for this process, its major drawbacks far outweigh the proposed benefits. Compression schemes such as Octree [Zeid] or Wavelet [Strang] exist. But, in order to use voxels at their fullest

potential, compression must not be done. Time will tell its outcome but right now a different type of model is necessary.

The CAD model representation that this research achieves is a commonly used file type called a boundary representation or Brep solid model. A Brep solid model is a closed surface model which means that each surface knows its neighbor and it is possible to traverse over the boundary of the entire object.

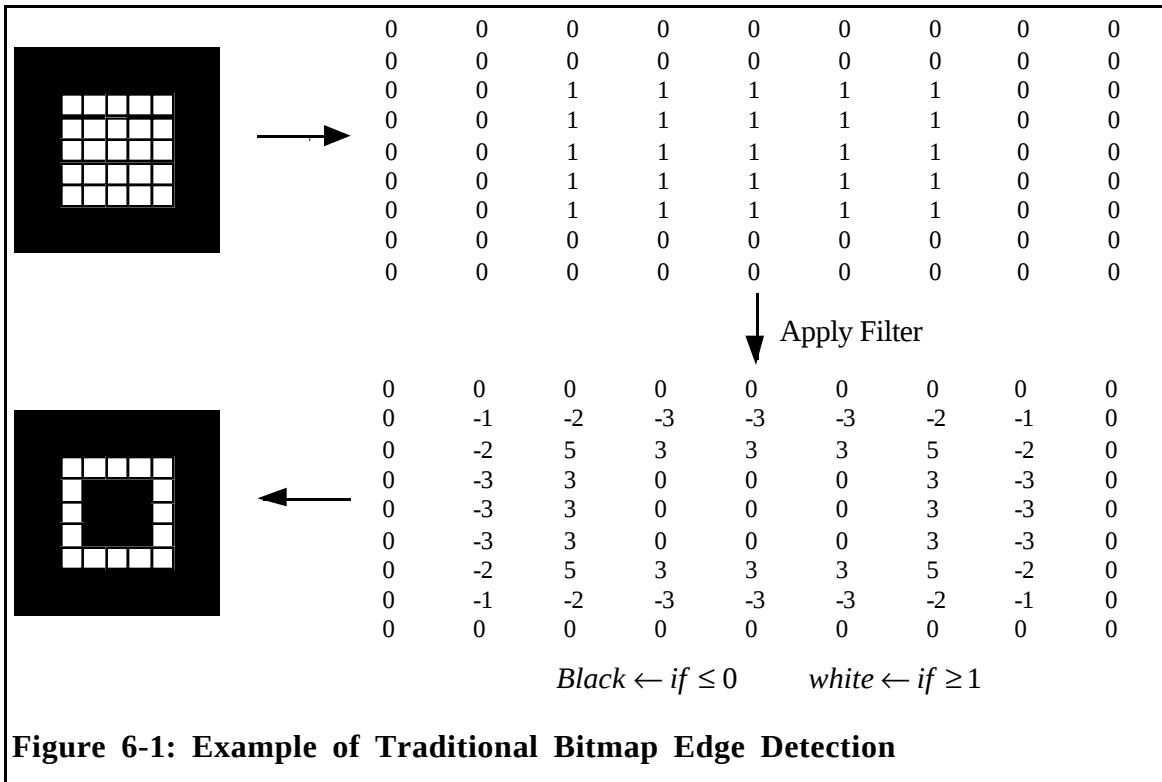
6.2 Boundary Points

6.2.1 Traditional Edge Detection

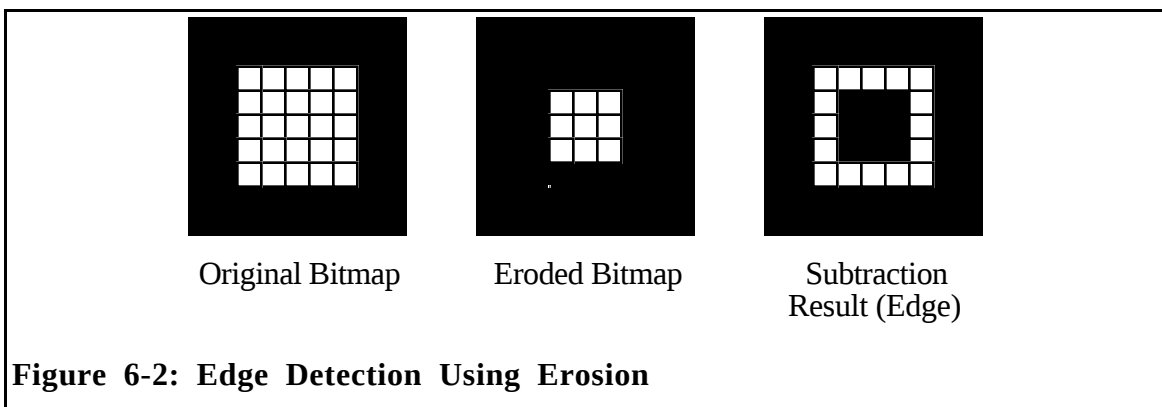
In section 5.4, the 8-bit gray scale images are simplified to a one bit representation. This helps the edge detection process dramatically. A traditional 2D edge detection algorithm uses a weighted sum filter like the one shown in Equation 6-1 where the a's are equal to one for on and zero for off. The final sum will always be an integer value. If the sum is one or greater then the pixel remains on and if the sum is zero or less then the pixel turns off. More elaborate schemes exist but this filter shows the simple essence of all similar algorithms. An example of this filter is seen in Figure 6-1.

$$\begin{pmatrix} -a_1 & -a_2 & -a_3 \\ -a_4 & 8 \cdot a_5 & -a_6 \\ -a_7 & -a_8 & -a_9 \end{pmatrix} \Rightarrow a_5 = 8 \cdot a_5 - a_1 - a_2 - a_3 - a_4 - a_6 - a_7 - a_8 - a_9$$

Equation 6-1: Bitmap Edge Detection Filter



Edge detection of bitmaps can also be accomplished using a method called erosion. Erosion is accomplished by expanding each black pixel to its eight neighbors regardless of whether they are white or black and saving that new image in a separate file. Thereby “eroding” one pixel width or in other words the edge pixels of the white image. This eroded file is then subtracted from the original image which leaves the edge of the original image because the difference of the two images is the eroded pixels. This edge detection method is demonstrated in Figure 6-2. An adapted 3D version of this method is used in this research.



Regardless of which edge detection method is used, two fundamental problems exist. The first is that 2D edge detection loses information for surfaces which are scanned parallel to the cutting plane. The second is noise in the data after edge detection. Both of these problems make it difficult to construct a 3D surface model and are talked about later.

6.2.2 3D Edge Detection

The 2D edge detection schemes talked about in the previous section work on individual images separately. For parts which have low spatial frequency (curvature changes very slowly) such as some free form objects, this situation would be fine. However, this requirement is a severe limitation to part geometry. In the case of the example block shown in Figure 6-3, it has high spatial frequency at all sharp corners. Because edge detection is done on the images individually, they will not contain any point information for those features parallel to the cutting plane such as the top and bottom. Therefore, when surfaces are matched to the points, the top, bottom, and all features parallel to the cutting plane will be lost. Even though the block is a simple part, it shows the same problem that more complex parts have. Figure 6-4 illustrates this problem using the simple block shape.

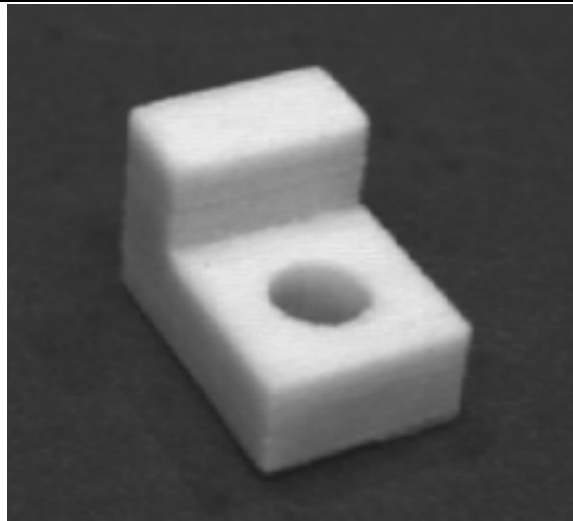
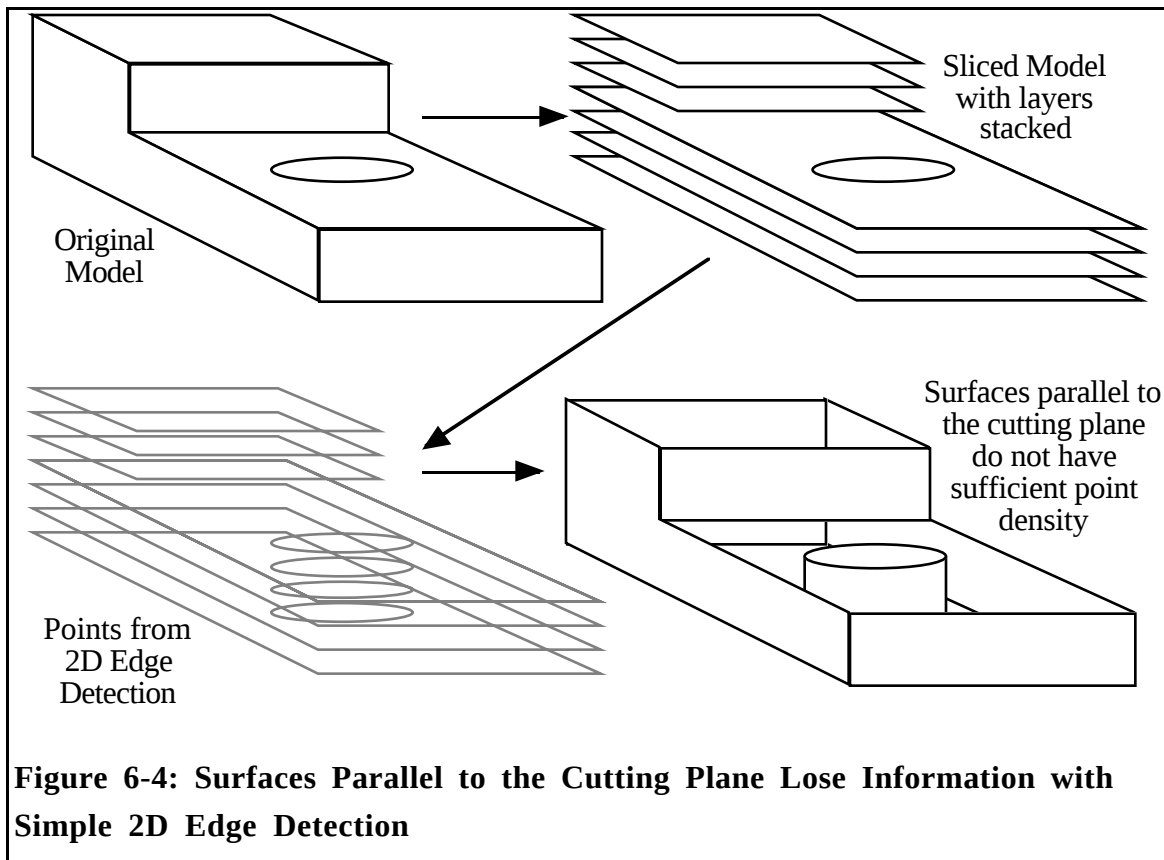
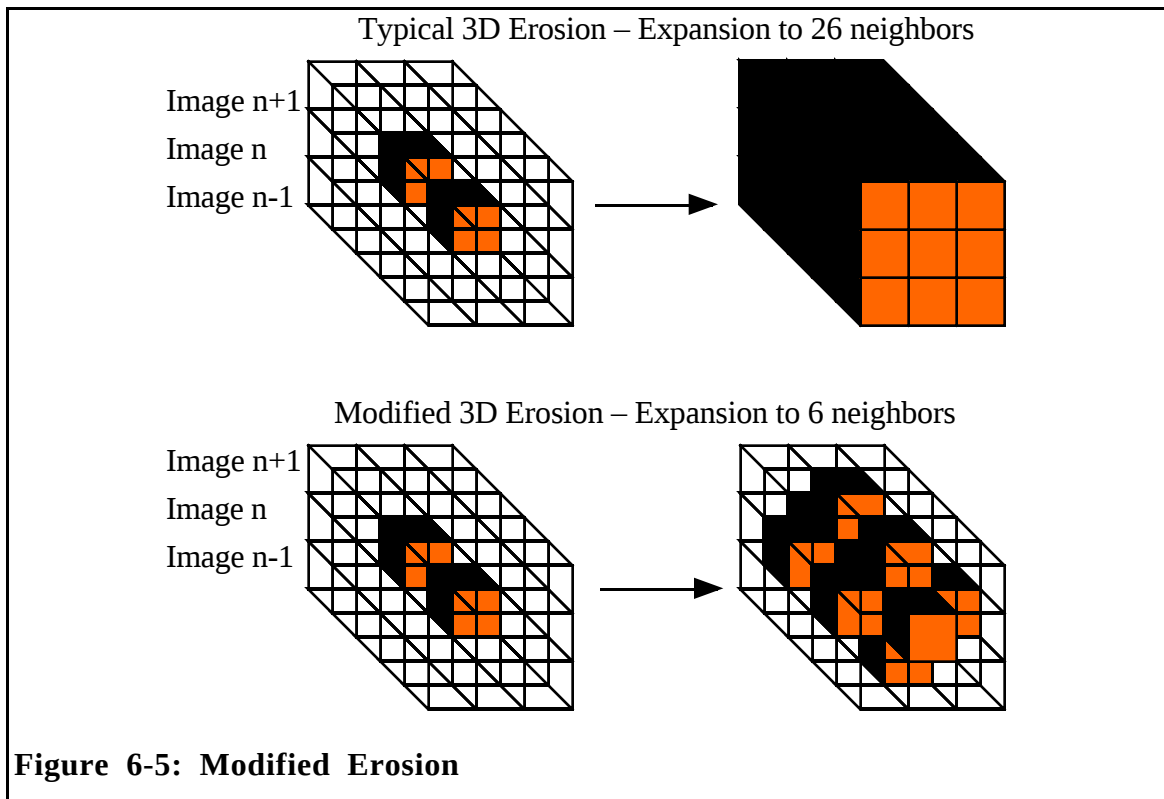


Figure 6-3: Simple Block with High Spatial Frequency



The most straightforward way to solve this problem is to adapt one of the previously described 2D algorithms to three dimensions and deal with the discrete part data as a whole rather than slice by slice. This way the information about the surface points parallel to the cutting plane is maintained.

The first algorithm that uses the weighted sum can be altered to a three dimensional matrix of twenty seven elements. The center coefficient is 26 and all the rest are -1. Erosion can be done by having each black pixel expand into its eight pixel neighbors and the nine directly above and directly below. The method used in this thesis is a modification of erosion. Instead of expanding into all 26 adjacent pixels, expand the pixel into only the six pixels along the three major coordinate axis as is shown in Figure 6-5.



This modification does not adversely affect the outcome of the subtraction. In fact, it decreases the required CPU time.

6.2.3 Noise Filter

As with any edge detection algorithm, noise is always a problem. Little specks in the images will remain after edge detection is complete. As far as the filter is concerned, noise specs are edges. The surface model construction talked about in section 6.3 can accommodate small variation in accuracy of the data points on a surface but performs poorly with gross errors.

A noise filter that isolates solitary pixels and eliminates them is called a despeckle filter. It works in two ways. If a white pixel has no white neighbors then it is removed. Likewise, there may exist a black point within the boundary of the part and it can be removed with a similar technique. This despeckle filter is found in such image processing applications as Adobe Photoshop. This filter works fine if the noise in the images only comes from single pixel error. But, if the noise is on the order of two or more pixels then they are not removed using the despeckle filter. Since noise is usually always bigger than one pixel in the scanned images, the despeckle filter is not used in this research.

Interestingly, it is possible to make a better noise filter using the 3D erosion algorithm described in the previous section. Erosion, along with its opposite partner algorithm dilation, can remove substantially large noise speckles while maintaining part integrity. Dilation is just like erosion except that it expands each white pixel to its 6 closest neighbors. The following step by step algorithm which uses erode and dilate eliminates noise both black and white from the image information. It finishes with subtraction as described in the previous section to get the surface data points.

1. Erode – Eliminates white noise in black regions.
2. Dilate – Returns images to original state without the white noise.
3. Dilate – Eliminates black noise in white regions.
4. Erode – Returns images to original state without the black noise.
5. Erode – Removes white edge pixels.
6. Subtract – Produces surface data point information.

This idea is difficult to demonstrate in three dimensions therefore Figure 6-6 illustrates these steps in two dimensions. The erosion and dilation is done by expanding to its four neighbors. Erosion first removes the noise outside the part. With two dilations, the noise inside the part is also removed. The process is finished off and the boundary points are found with two more erosions and a subtraction. Refer back to Figure 6-5 to visualize how the 3D version would work.

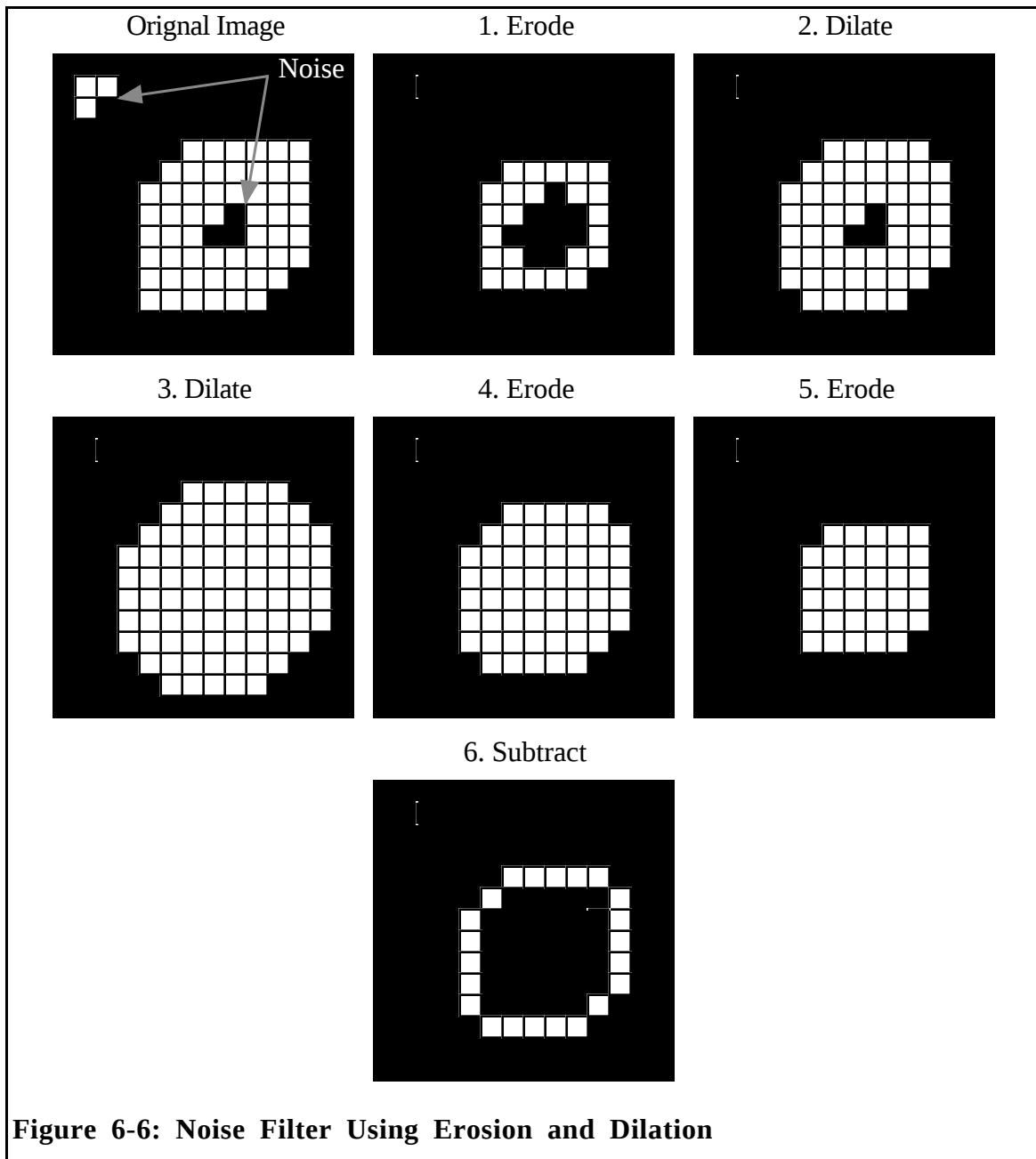
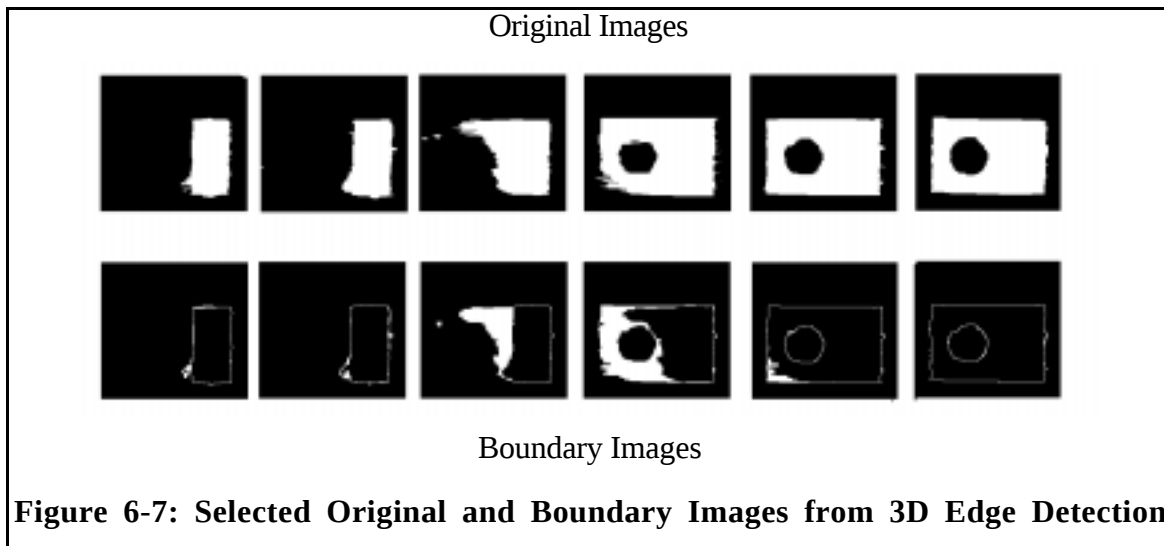


Figure 6-6: Noise Filter Using Erosion and Dilation

This example is only to demonstrate the concept of the filter. The real data sets are hundreds of pixels in all three dimensions. This example also clearly shows one remnant of the filter and that is the missing pixel on the two 90 degree corners. In the three dimensional filter, any pixel edge point at a sharp 90 angle will not be left after the filtering and edge detection. While this may seem like a problem, it is not because there is still ample information to create the geometry of the part.



Filtering and edge detection is a computationally simple yet long process. With reading and writing buffer information and error checking, it may take one hour of CPU time to produce a proper data set from a moderate sized part. Since the file size of the part increases by N^3 , time is an issue which must be met if extremely large parts are going to be designed with the design cycle. Selected images of a digitized block in original and boundary form are shown in Figure 6-7. Notice the middle images where the information at the cut in the block is retained.

6.2.4 Point Reduction

After the boundary points have been found, a surface model can be created. However, eliminating redundant point information is very helpful in simplifying the construction process. Take for example the boundary points found for the block (see Figure 6-8). For this particular block there are 54,716 points on the surface boundary. This is far beyond what is necessary for this simple block shape.

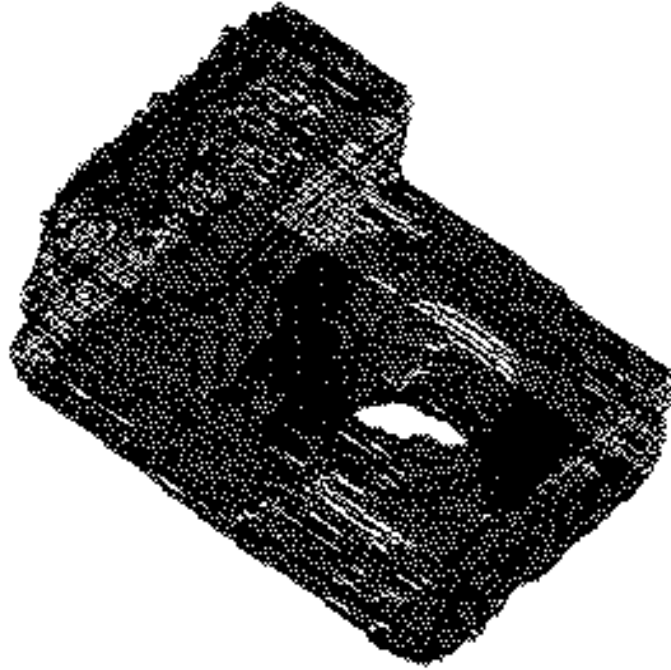


Figure 6-8: 54716 Boundary Points for the Digitized Block

In section 6.3, Points to Surface Model, there is a parameter which must be intelligently set. This parameter is the minimum distance between two parallel surfaces. Recalling the idea of minimum sample rate from signal processing, the Nyquist sampling frequency must be 2 times the minimum frequency component of a signal. It is also recommended that for good measure and to help eliminate magnitude attenuation, the minimum sampling frequency should be 4 times to 5 times the minimum frequency component of a signal. In this research the frequency is surface frequency and the period of minimum surface frequency is the minimum distance between two parallel surfaces. Therefore, there must be at least point density 2 times minimum sheet spacing and better to have 4 times the point density.

$$n \leq \frac{(R) \cdot (S)}{d}$$

n = Axis Reduction Factor (Integer Value)

R = Resolution (i.e. 300 dots per inch (dpi))

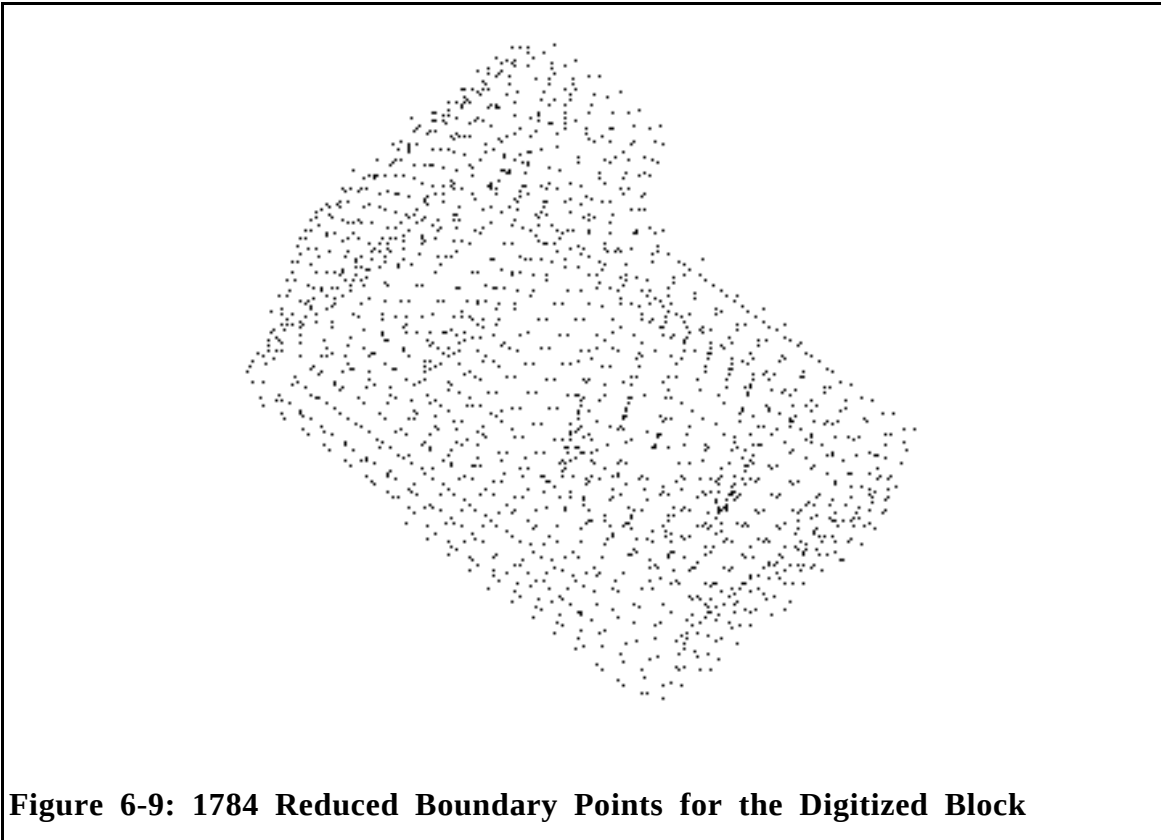
S = Minimum Surface Spacing (inch)

d = Points between required between S (d=4 recommended)

Equation 6-2: Reduction Factor

Equation 6-2 can be used to calculate a reduction factor “n”. “n” is an integer value which corresponds to the number of white pixels needed in succession along a certain axis (n_x , n_y , n_z). The reduction algorithm works on one row, column, or vertical column at a time. For example purposes, a row reduction is explained. The row is offset from the top of the image by an integral number of n_y . It is tested point by point for a white pixel. When a white pixel is found, the test skips the next n_x pixels in that row then continues testing. At the end of that row, the tests begin in a new row which is offset n_y down from the row just finished until the image is complete. Next a new image which is n_z from the completed image is tested. This test must be done for each image in the three major axis: X, Y, and Z. It is important to note that setting up a simple cubic grid and testing for a white pixel at each node in the grid will not give proper results.

Using the block points as an example, the X axis and Y axis are scanned at 300 dpi and the Z axis is cut at 0.010 inches or 100 dpi. Therefore, if the minimum spacing is 0.12 inches and using $d = 4$, the reduction factor equation results in $n = 9$ for the reduction factor in the X and Y axis and $n = 3$ in the Z. The images are resampled at these intervals which give a good reduction of points. For the block there is almost 2 orders of magnitude reduction to 1784 points.

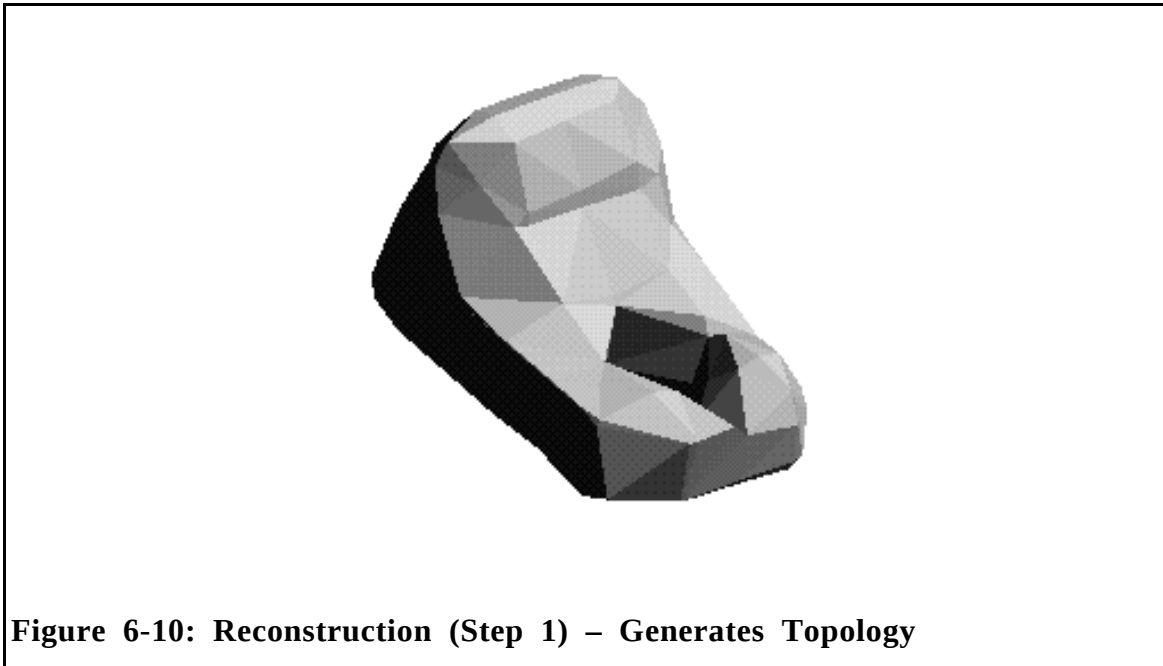


6.3 Points to Surface Model

From 1991 – 1994 a group at the University of Washington worked on the problem of creating surface models from unorganized data points. Their method goes through three steps and each of these steps has been published in SIGGRAPH 92, 93, 94 [Hoppe et. al.] respectively. The first step is rough model generation which simply gets the topology of the data set, the second is an optimization of the surface by pulling the polygons found in step one closer to the actual data points, and the third is a piecewise smooth surface fit. The descriptions of the procedures is taken from the abstracts of the respective papers.

Step one, “takes as input an unorganized set of points $x_1, \dots, x_n$ subset $\mathbb{R}^3$ on or near an unknown manifold U , and produces as output a triangulated polyhedron that approximates U . Neither the topology, the presence of boundaries, nor the geometry of U are assumed to be known in advance --- all are inferred automatically from the data.” In other words the goal of this step is simply to determine the topological type of the surface and to produce a rough estimate of its geometry. The method for step 1 defines a function $f: \mathbb{R}^3 \rightarrow \mathbb{R}$ that estimates the signed geometric distance to the unknown manifold U , and then using a contouring algorithm (modified version of the marching cubes algorithm

[Lorensen]), extracts an approximation to its zero set, $Z(f) = \{p \in R^3: f(p) = 0\}$. The one user input to this step is the minimum surface spacing also talked about in Point Reduction section. Figure 6-10 shows the result of step 1 using the reduced data set taken from the block in the previous section.



With step 1 complete, step 2 attempts to solve the following problem: “given a set of data points scattered in three dimensions and an initial triangular mesh $M-\{o\}$, produce a mesh M , of the same topological type as $M-\{o\}$, that fits the data well and has a small number of vertices.” Their objective function is defined as the minimum “energy function that explicitly models the competing desires of conciseness of representation and fidelity to the data.” The variables for the optimization consist of the number of vertices in the mesh, their connectivity, and their positions. The optimization search space is all meshes of the same topological type as that produced in step 1 and this search space is traversed “using a set of mesh transformations (edge collapse, edge split, and edge swap) that locally modify the mesh connectivity.” The optimization also tries to reduce the number of necessary polygons. As can be seen in Figure 6-11, this produces a much better model of what the data represents. Similar research was done at the Iowa State University. Their goal was also to simplify the polygon mesh while maintaining topological and surface constraints [Renze].

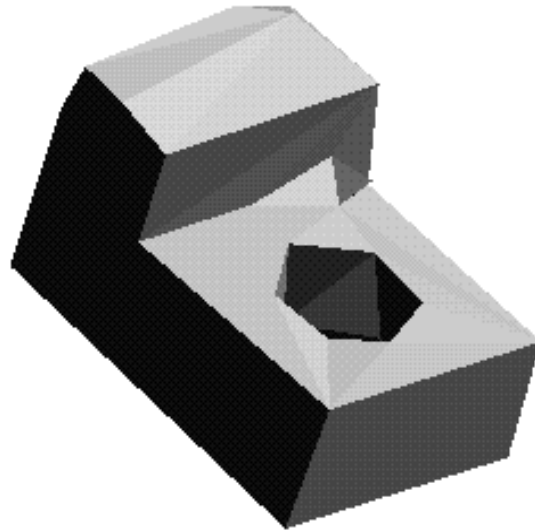
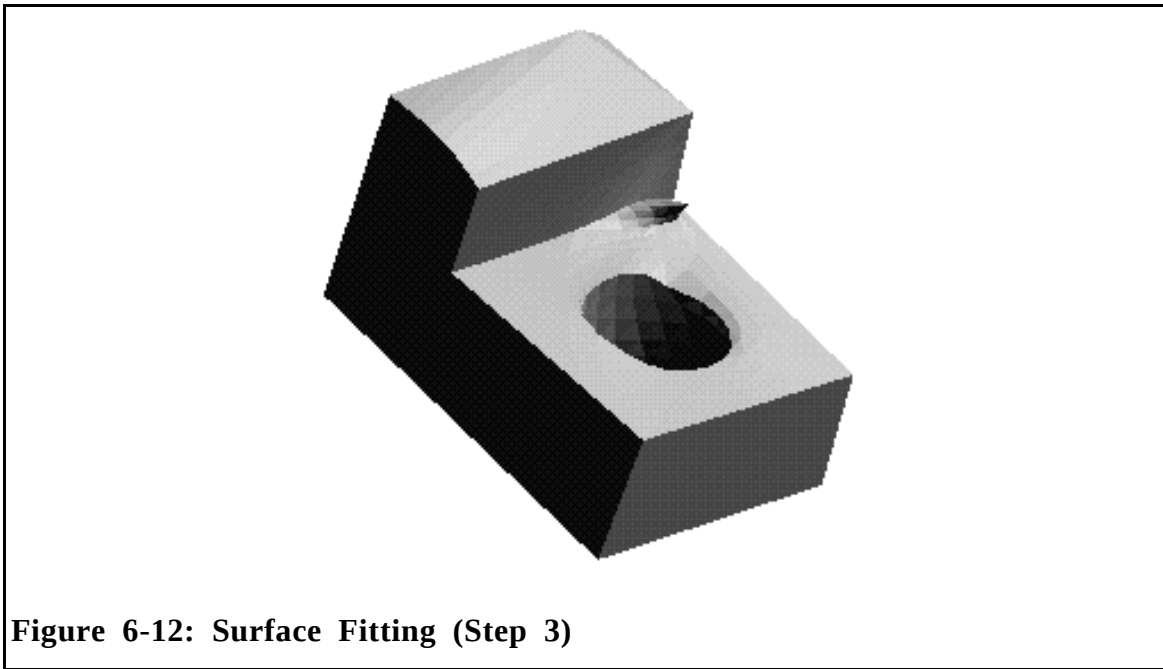


Figure 6-11: Optimization (Step 2)

The output of step 2 in many cases gives an adequate representation of the original model. However, for freeform parts, the large polygonal output may be somewhat “chunky” and a better representation is required. Creating a better representation can be accomplished with a possibility of two methods. Both are based on a new class of smooth surface representations. The first is a deformable surface patch [Celniker and Gossard] and the other is a surface representation based on subdivision [Hoppe et. al.].

The deformable surface patch uses a finite-element solution technique which yields a continuous mathematical description of a surface over a triangular region. This patch can be deformed using mathematical forces (pressure or point) and best fit to data points. This representation of the electronic model may in the future be implemented. However, current computer models in use with rapid prototyping machines are based on a polygonal representation. Therefore, when generating an electronic model from scanned data it is presently adequate to leave that model in polygonal form and the surface representation based on subdivision is used. This representation subdivides each polygon in the optimized mesh into several smaller polygons. This was first introduced at the University of Utah [Loop] and generalized to include rules for sharp corners by the group at the University of Washington [Hoppe]. The subdivided polygons can deform to better fit the data. As can be seen in Figure 6-12, the subdivision creates a surface which closely represents the physical model. The visible error represents a bubble trapped on the surface of the part during

embedding. (This scan was not done with the recommended materials discussed in chapter 5.) This error is corrected in Figure 6-15 on page 77.



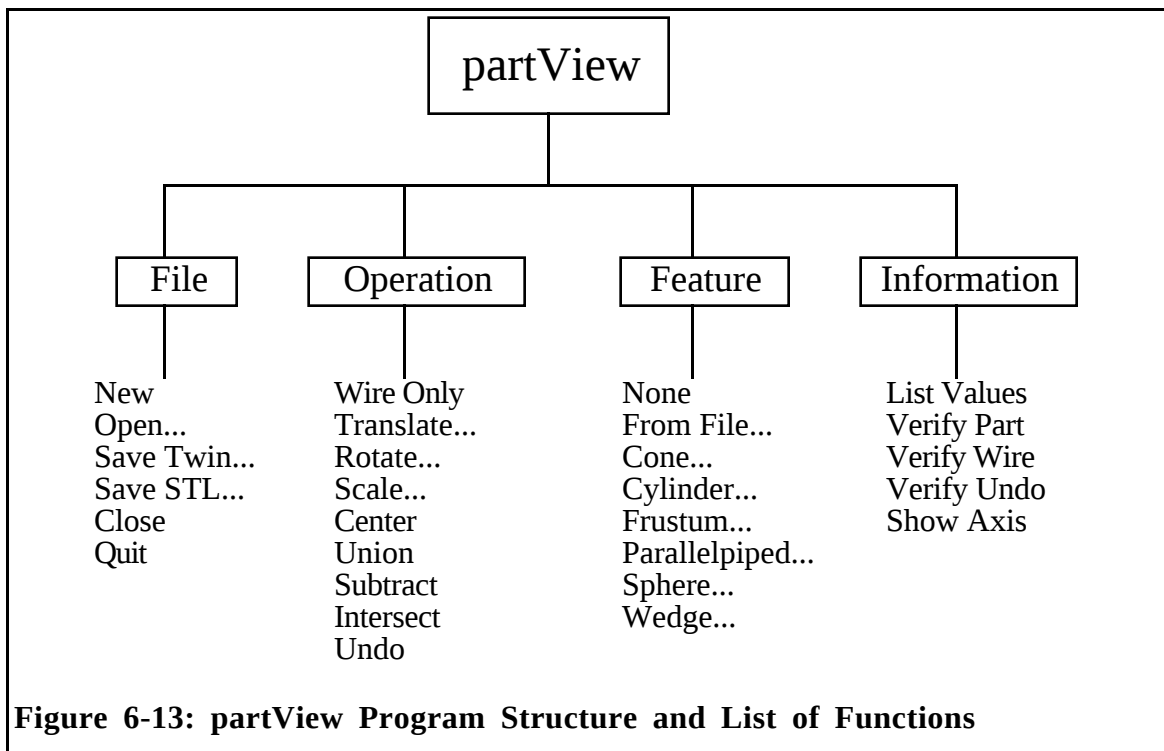
6.4 Surface Model to Solid Model

The output of the points to surface model section is a set of polygons which describe the model. If the three surface reconstruction algorithms start with a complete data set fully dense on all surfaces, the output describes a closed surface. Therefore the topology can simply be rescued from the polygons and put into a “useful” data structure. There is commercial software which works strictly with polygons. It is called FormZ created by Autodesk, Inc. based in Columbus, Ohio. This software puts the data into its proprietary format and then can be manipulated by a user. Since the data is in a proprietary format, further extension and research using FormZ can not presently be done and therefore is not used in this research.

In this work, the set of polygons is decomposed into points, edges, and polygons and written into a file format called TWIN developed by the CADlab at the University of Purdue. A sample of the TWIN file format is found in the appendix. The TWIN file format is a Brep solid model and the data is no longer a simple surface model. Once converted, the model is ready to be manipulated with traditional CAD tools such as Boolean operations.

6.5 Boolean Operations

Custom software with a user friendly interface is written in order to perform simple Boolean operations and other functions. The program organization and function capabilities are listed in Figure 6-13 and the user interface is shown in Figure 6-14. The program is subdivided into four menu options with several functions in each. Most functions are self-evident. The Information menu gives the status of various parts of the program and is useful for debugging purposes. The three dots after the functions note that there will be a pop up window or that the function will need user input to continue.



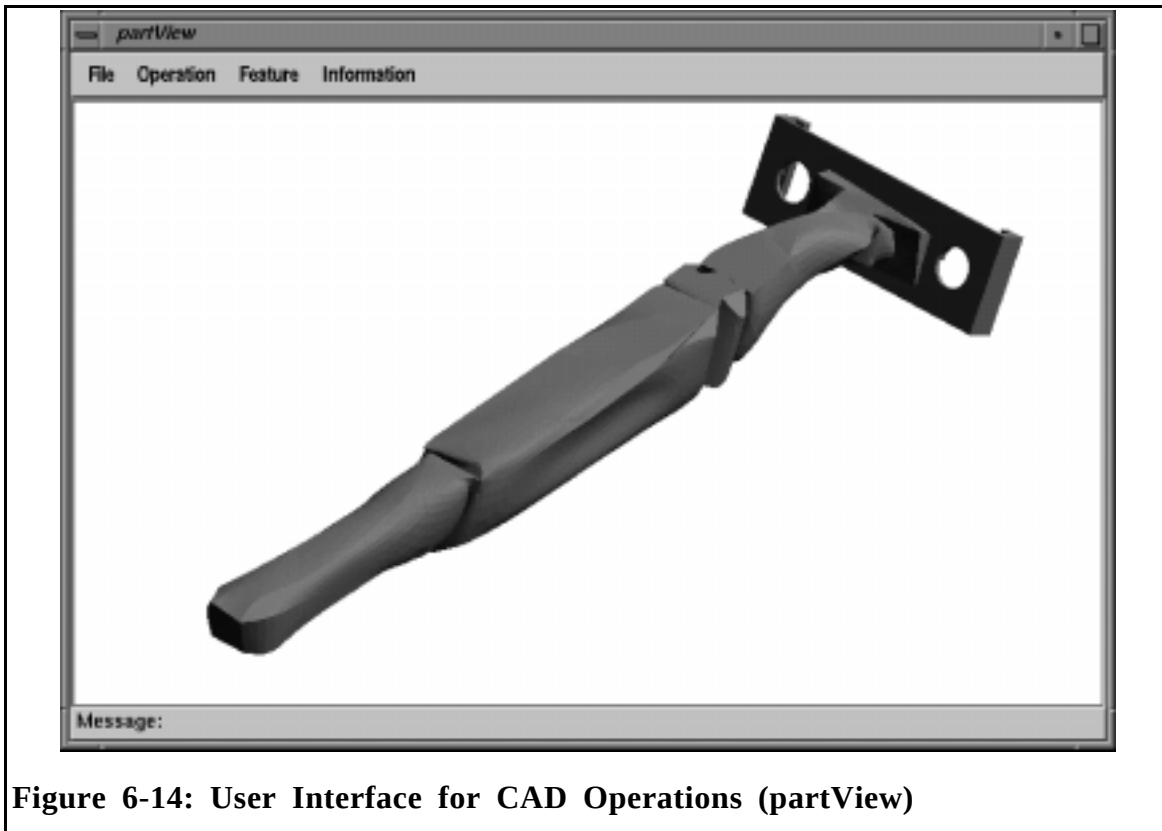


Figure 6-14: User Interface for CAD Operations (partView)

The partView software is capable of removing an error in the block as seen in Figure 6-15. This fix is done by subtracting a parallelepiped which is exactly parallel to the two surfaces that the error touches.

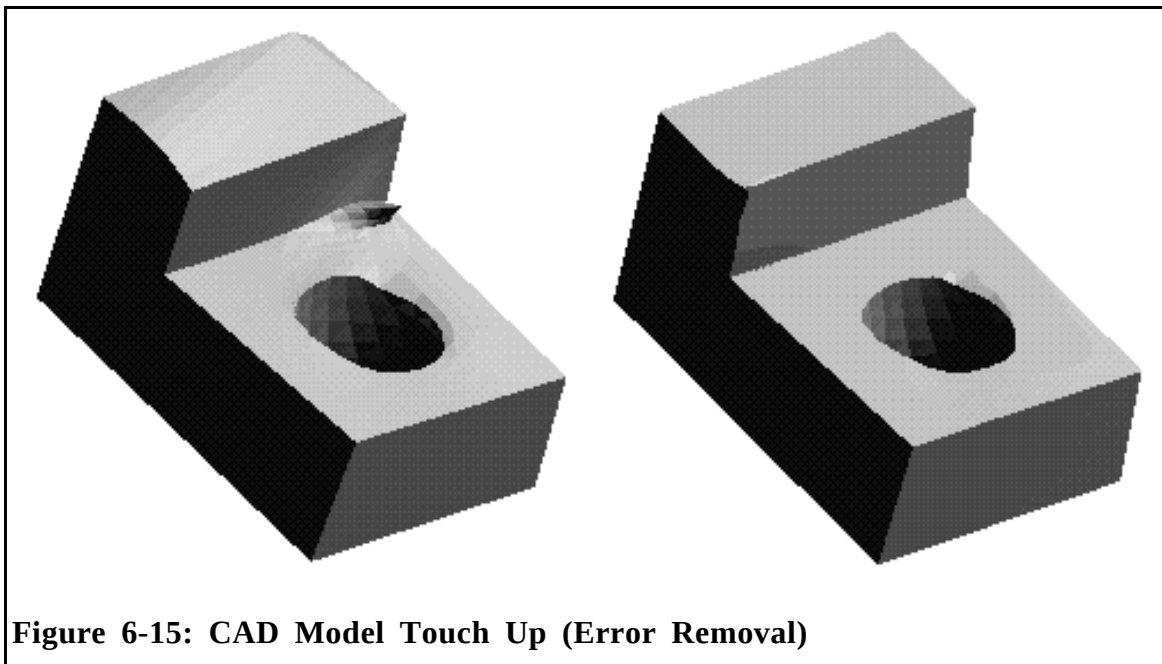
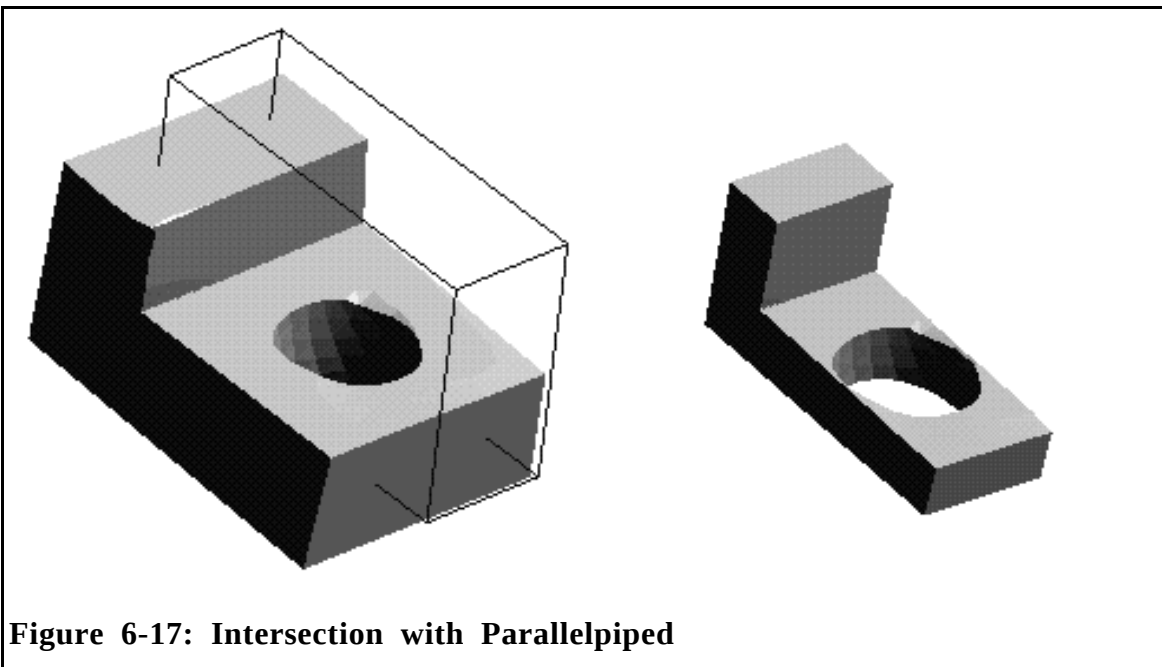
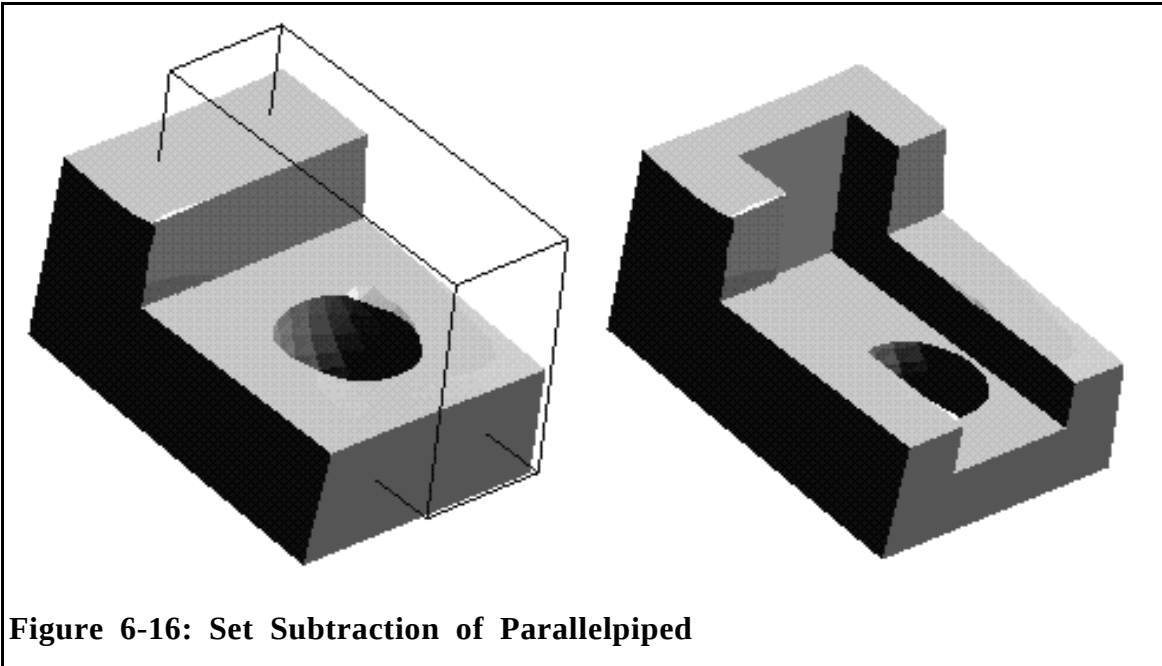


Figure 6-15: CAD Model Touch Up (Error Removal)

A better example of how the Boolean operations can be utilized is demonstrated in the next series of figures. Figure 6-16 shows a block and parallelepiped together and then a groove is cut by subtracting the parallelepiped.



By performing an intersection with the same setup, a slider which exactly fits in the groove can be created as seen in Figure 6-17.

Small knobs can be added to the back of the groove to help secure the slider in Figure 6-18. This is done by performing a union operation.

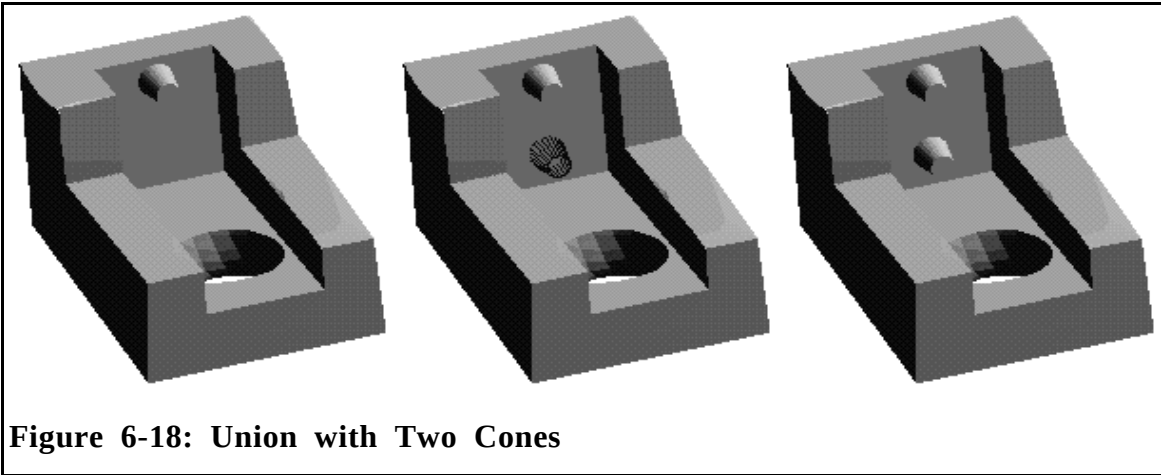


Figure 6-18: Union with Two Cones

Even though this is a simple example, it is important to note that one complete loop of the design cycle is now completed. The block started as a CAD model, physically created by 3D printing, digitized and returned to an electronic medium. Since these CAD models can be easily saved into the standard rapid prototyping file format .STL, the cycle can go on indefinitely.

Chapter 7

7. Applications

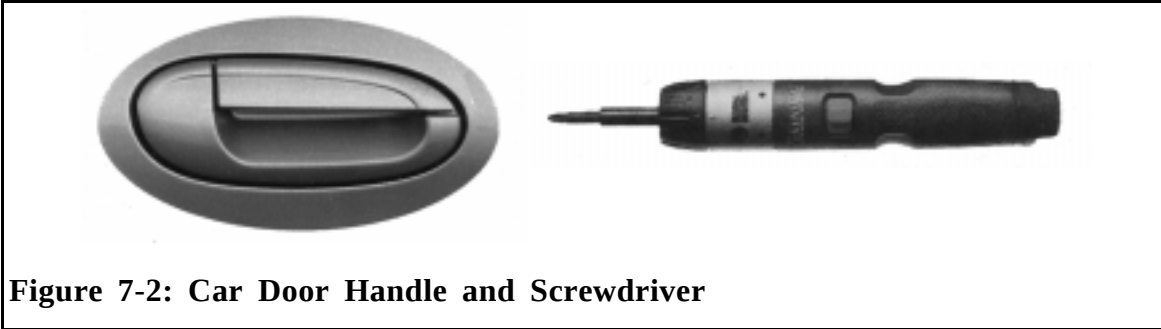
7.1 Subjective Design

One of the main applications of this design cycle is the ability to design parts which have both subjective contours and functional constraints. The design cycle has the unique ability easily work with basic geometric shapes as well as free form surfaces. The basic geometric shapes with precise mathematical descriptions like cones, cubes, etc. are best created in an electronic environment. It is difficult to create freeform shapes in the computer and is much more suited to creation by sculpting a physical model.

Many consumer handheld objects fit into this category of having subjective contours as well as geometric and kinematic constraints. Figure 7-1 and Figure 7-2 show three possible candidates: a handheld razor, a car door handle, and a screwdriver. Others examples include an electric razor, a computer mouse, and a telephone handset. There are many more.



Figure 7-1: Handheld Razor



The car door handle is a perfect example of aesthetics combined with functionality. The exterior must be both aesthetically pleasing as well as have the right “feel”. It is also connected to a kinematic linkage that opens the door. The look and feel of the door are subjective qualities and are best designed with a physical model. The linkage is made up of typical geometric shapes and is best created in the computer where dimensions can be defined precisely.

The design cycle also applies well to the creation of the screwdriver. While the screwdriver in Figure 7-2 is somewhat simple, the exterior could be very complex to make it more ergonomically sound. A parting line must be defined and mounts need to be created in the interior for the motor, battery, switches, etc.

As a demonstration of the functionality for the design cycle, it is used to create a new razor handle. The important part of the demonstration is not the finished razor. The important part is the design process and recognizing the contribution the design cycle makes to the design of complex 3D shapes.

The demonstration begins in the computer where the rough shape of the razor is quickly blocked out into a CAD model which took approximately 10 minutes. Using Three Dimensional Printing, the model is created in the glass powder and wax composition and an industrial designer carves and reshapes the model into a complex shape. When modification is complete, the physical model is digitized and converted into a polygonal Brep CAD model where the head of the razor is added.

Figure 7-3 shows the razor in its blocked out form as a computer model. Only major features are included.

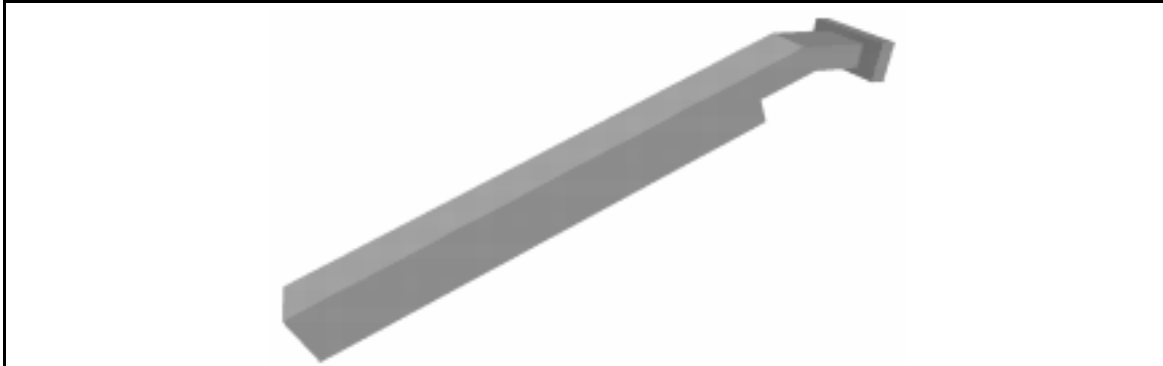


Figure 7-3: Beginning CAD Model

The CAD model is used to produce several physical models by 3D printing and wax infiltration (Figure 7-4). This gives the designer freedom to think and design freely.

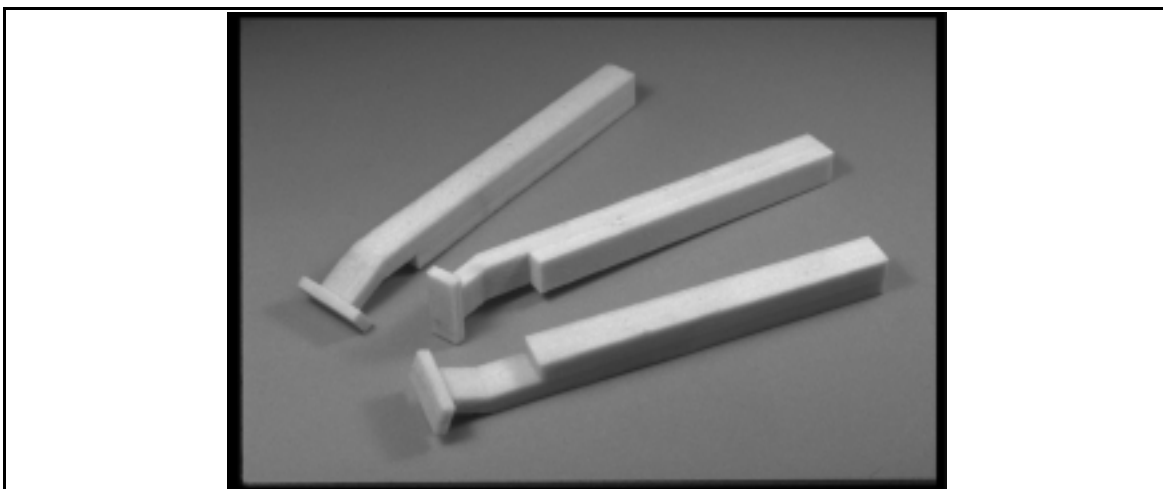


Figure 7-4: 3D Printed and Infiltrated Razor Handles

An industrial designer drew rough sketches of possible concepts then carved those ideas in Figure 7-5 and Figure 7-6. He used a simple carving knife and each razor took just under 1 hour to make.



Figure 7-5: Razor Modified Using Hand Tools



Figure 7-6: Second Modified Razor Using Hand Tools

The design shown in Figure 7-5 is picked as a good concept and is digitized. The slice thickness is 0.01 inches and each layer is scanned at 300 dpi. Just over half an inch (52 images) is sliced and scanned. Custom software called “boundary” is used on the images to align to the reference marks, filter out the noise, create a full boundary point representation and reduce the number of points required as defined by the minimum surface spacing. The output is 5942 points on the surface of the digitized part. Figure 7-7 show the data points after being reduced.

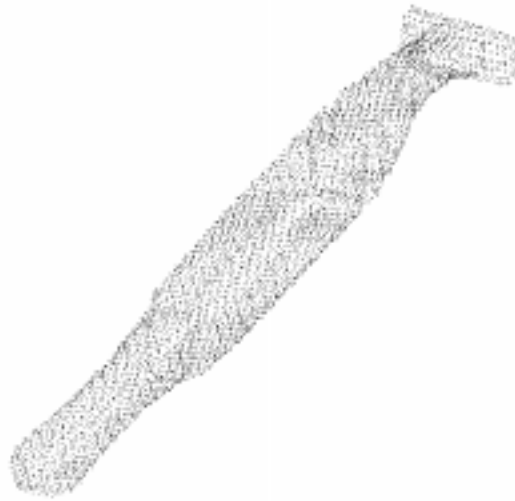


Figure 7-7: Digitized Data Points of Razor

A polygonal Brep CAD model is created from the data points by using the three steps of the reconstruction method discussed in chapter 6 and is shown in Figure 7-8.

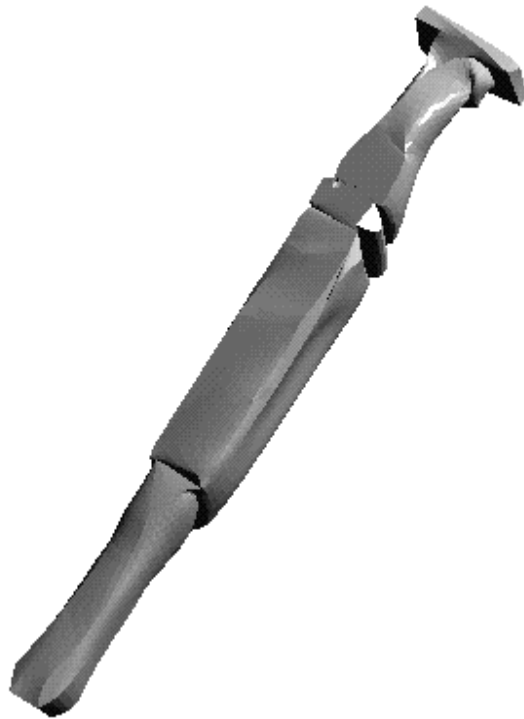


Figure 7-8: Razor CAD Model

The razor head in Figure 7-9 is a holder for certain types of disposable razor cartridges. For example, this head might be standard across all the razors for a certain. In order to complete one iteration of a design, the head must be unioned with the razor body design. The result of the union operation is shown in Figure 7-10.

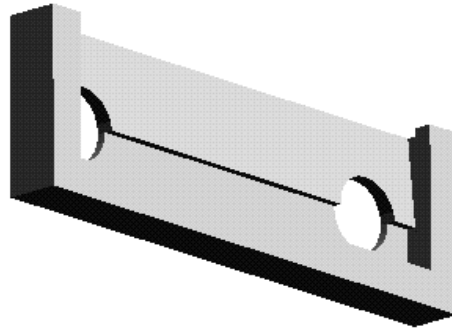


Figure 7-9: Razor Head Design

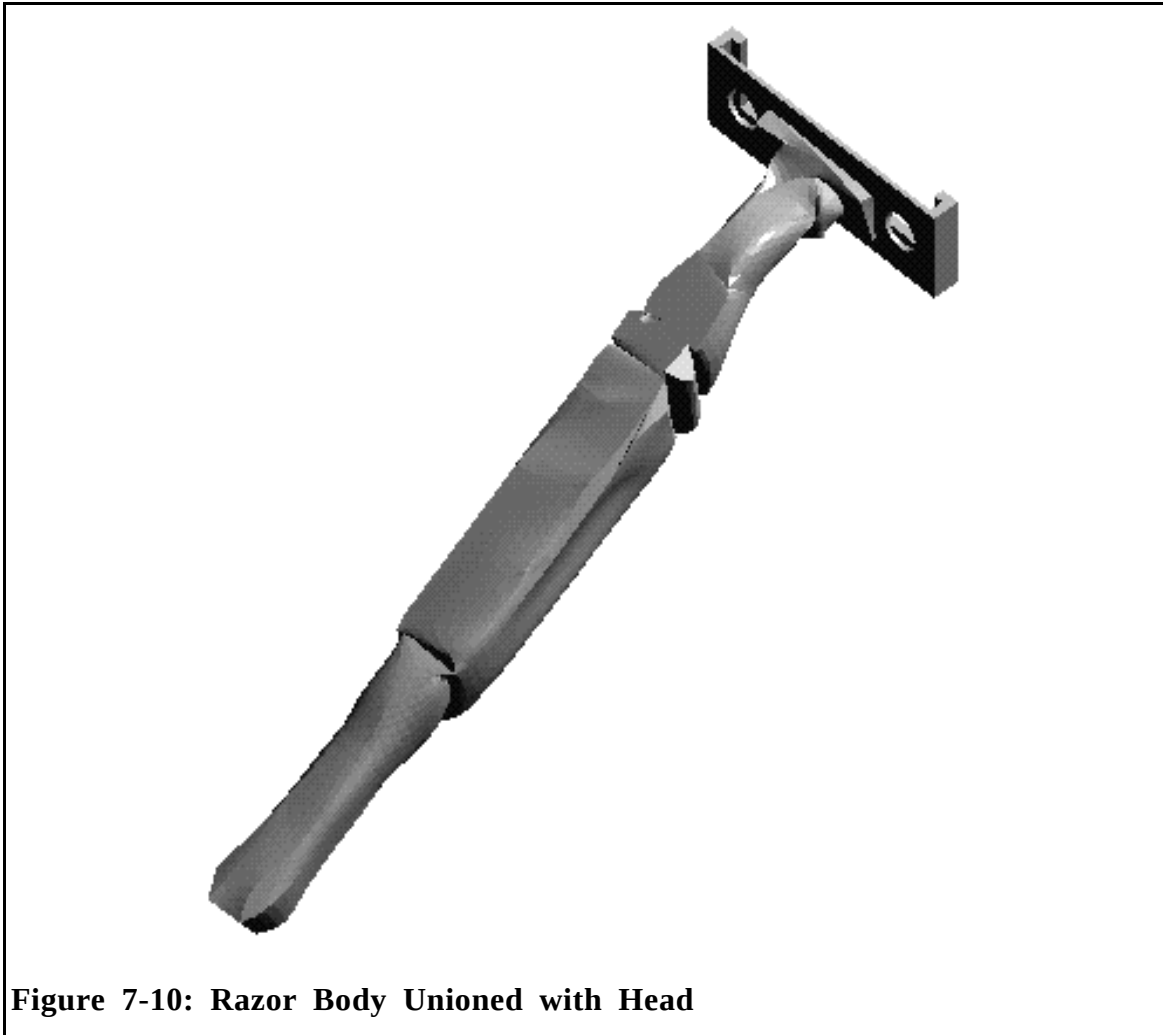


Figure 7-10: Razor Body Unioned with Head

This example demonstrates the use of the design cycle. It allows the designer to use the model, physical or electronic, which can best implement a design idea. The complex surface of the body is made with the physical model and the head is completely designed in the computer and both are combined into one model. This design is created quickly and efficiently. This gives the designer more time to design rather than spending time on figuring out how to design.

7.2 Assembly Design

As described in the previous section, subjective designs with constraints can be extended to assembly design as well. There are many assemblies that have two or more parts that mate and form a continuous subjective contour. Commonplace examples of this type of design are cameras, walkmans, cellular flip phones, and camcorders.



Figure 7-11: Subjective Shape Assembly Examples of the Design Cycle

For this type of design, the freeform shape can be designed irrespective of the assembly. Obviously, there are internal geometry constraints but as long as all internal features can fit inside a certain volumetric envelope then the exterior design can be placed in whatever manner on top of that envelope (see also section 8.1.3 for further discussion about internal constraints). After the exterior is designed, then the assembly features can be extracted.

This type of design can be applied to the camera shown in Figure 7-11. After the smooth exterior shell is created using a physical model, the shape of the flash and its pin connections can be created in the CAD model. This way, the assembly is still guaranteed to be flush. The same technique can also be applied to the film door in the back.

A walkman, diskman, flip phone, and camcorder can all be designed in a similar fashion. The most important point to remember is that the time necessary to do this design is shorter than the standard practice. Many designs can be explored quickly and efficiently.

7.3 Medical Visualization and Design

Physicians at the Massachusetts General Hospital and also at Brigham and Women's Hospital expressed interest in the design cycle. Medical visualization using high end computer graphics is becoming an important tool for doctors. Computers allow them to see and diagnose problems that were previously impossible. However, just like engineers, doctors sometimes need physical models to help them understand and visualize a problem and subsequently develop a solution. Physicians also use models to explain problems to their patients. For example orthopedic surgeons often have models of typical knees, elbows, and other joints to show patients what has happened to their body and then

describe the surgical procedure that will be implemented. Internal medicine physicians have models of typical organs for the same purpose.

The design cycle can be used in the medical field for two purposes. One is visualization. Computed tomography (CT) scanning and magnetic resonance imaging (MRI) capture information about the human body in volumetric form. These two procedures capture information about the human body in volumetric form in a section by section method but is non destructive like the scanning method employed in this thesis. CT scanning, MRI, and destructive scanning all produce the same type of data set. Therefore, using the methods of the design cycle described in chapters 5 and 6, computer models of organs, bones, etc. inside a human body can be generated. Subsequently, these models can also be translated into physical models quickly and easily. Figure 7-12 shows a physical model of a human liver section generated from CT data. (The CT data is courtesy of Dr. Ron Kikinas and Dr. Michael Halle of Brigham and Women's Hospital.)



Figure 7-12: Physical Model of a Liver Section

Another medical area the design cycle can assist is in orthopedic and reconstructive (plastic) surgery. The design cycle makes it possible to produce custom implants for joint replacements such as knees or hips and also for plastic surgery implants. For example, a person might be involved in an accident and shatter the Zygomatic bone (cheek bone) on the left side. A custom implant can be made by creating a CAD model of the cheek bone on the right side and doing a mirror algorithm and subsequently creating the physical part. Even though human's faces are not symmetric, this model copied from the right cheek bone would be a much better starting point for the surgeon than nothing at all.

Whether or not there is a market for this type of custom work is another question especially with hospitals trying to cutback on medical expenses. However, 3D printing has unique

manufacturing capabilities such as the ability to manufacture macro-texture on free form surfaces. Figure 7-13 shows two such examples. One is a torus with a mushroom field and the other is an artificial hip stem with texture to aid in bone ingrowth.

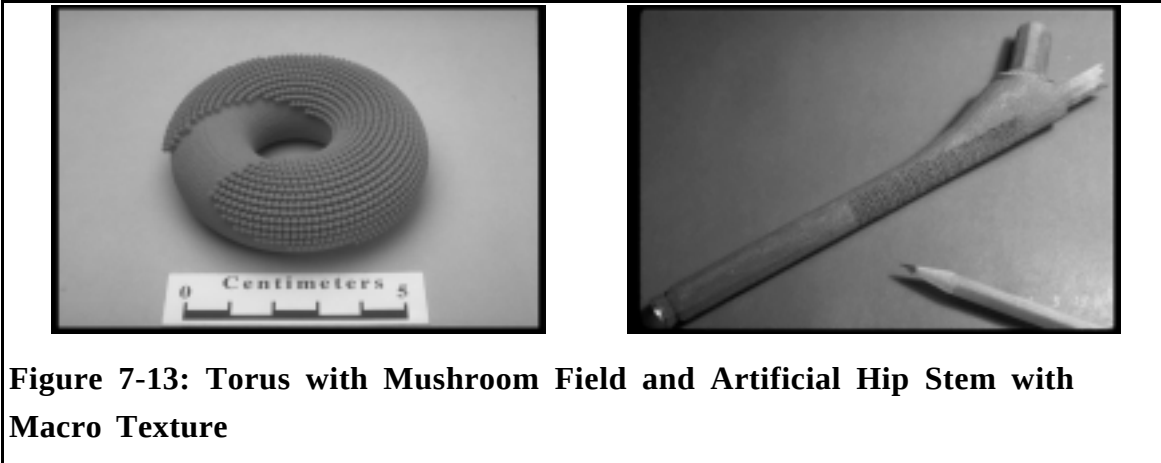


Figure 7-13: Torus with Mushroom Field and Artificial Hip Stem with Macro Texture

Further applications to the medical field are described in the future work chapter on page 97.

7.4 Design Iterations

The three previous examples of the design cycle have demonstrated short examples which may traverse the loop once. Design is not just a do it once and stop activity. It is naturally an iterative process. Design is done over and over. Changes are made to a design. A design may revert back to an older idea. A design may even be scrapped and a new one will start over fresh. The power of the design cycle allow a designer to enter the cycle with either of the modeling mediums (physical or electronic). Below are two more ways that the design cycle might be entered.

Design of a mating part – A designer may need to design a part to mate with another part that exists as either a physical or electronic model. An electronic model for a mating part can be used to establish boundaries on the part to be designed and the cycle can proceed. A physical model for the mating part can either be digitized or used to define the boundary of the physical part.

Redesign of a part – The designer starts by calling up the CAD model for the part in last year's model. Minor changes can be done directly in the electronic model and a physical

mode can be printed for verification. Major changes might better be accomplished by printing a physical model of the part and then manipulating the physical model. The changes would then be digitized and captured in electronic form. Finally, precise specifications could be added electronically.

The second example is interesting because it gives various options for editing the design. That is the way the design cycle should be used. The design cycle need not always be followed in every case. Take for example the part shown in Figure 7-14.



Figure 7-14: Complex Part from Ski Binding

The part may be printed out and the designer, in trying to place it in the proper assembly position, notices that one hole is the wrong dimension and in the wrong place. Rather than try to modify the physical model, the electronic models should be altered. This little jump bypasses one step in the design loop. Changes need to be made to the model that can most easily represent the changes.

The design cycle is not a tool which constrains the designer to work in one particular way. It is a powerful, liberating tool which allows the designer to be creative and to easily use the models at hand to express their concepts.

Chapter 8

8. Future Work and Conclusions

8.1 Future Work

Even though a working design cycle now exists and different applications can be explored, it is still in a fundamental state and many improvements and additions should be made to both software and hardware. Along with specific tasks that must be completed, ideas for further application can also be explored.

8.1.1 CAD

8.1.1.1 Shape Features

A major task will be to develop software methods to enable the user to identify and modify “shape features”, e.g. planes, cylinders, pockets, etc. Such “shape features” are higher-level descriptors of the CAD model. They play an important role in efficient shape editing during CAD model creation and modification because they describe a model in a higher level language which is closer to the way that the designer thinks about it. Shape features also play an important role in down-stream manufacturing applications that use the CAD model.

Software tools can be envisioned which enable the user to designate distinct regions of the model, apply constraints to that region (e.g. planar, cylindrical, etc.) and have the model adjust to those constraints. Similar work is being done by researchers at the University of Utah.

For the design cycle extracting shape features from the reconstructed CAD model poses a particularly difficult task. Since a designer is modifying the physical model by hand, the intent of the designer may be different than the physical model created for prismatic shapes. For example if the designer intends to make two surfaces perpendicular, but actually carves them to be acute or obtuse, the reconstructed CAD model will have off-perpendicular

surfaces. In this case the designer could edit the surfaces to be perpendicular, but creating CAD models which capture the designers intent from digitized data is an interesting avenue for future research.

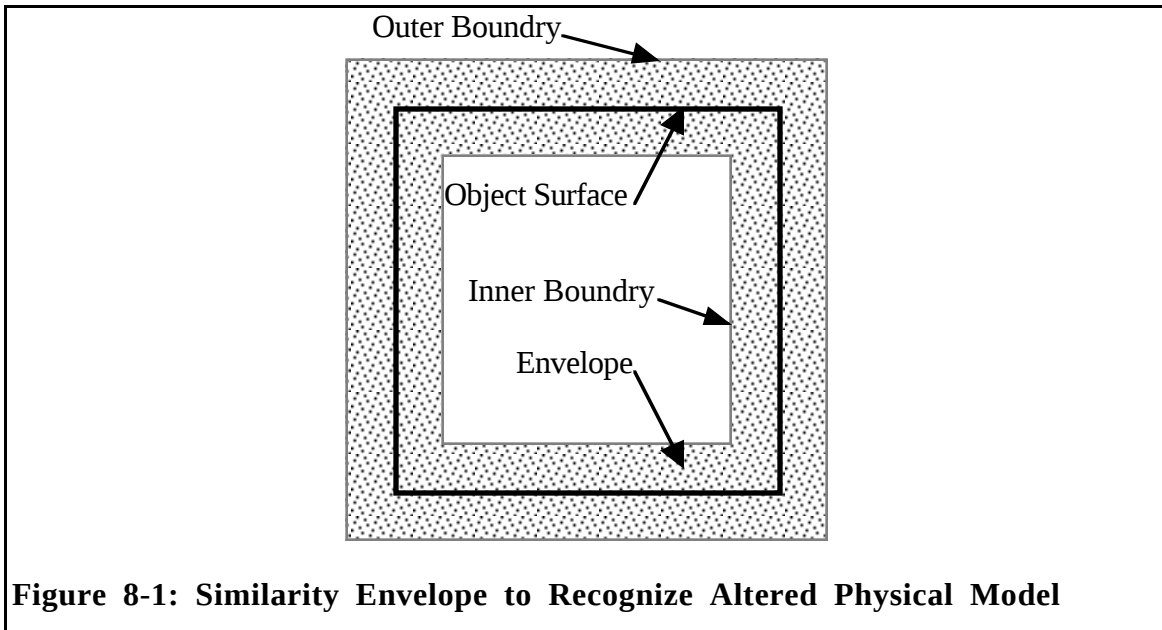
Often physical and electronic models have a plane of symmetry. If such a model is carved by a designer, it may not actually be symmetric because humans have difficulty making perfectly symmetric objects. However, it is conceivable that the designer could define a plane of symmetry in the reconstructed computer model. The two halves of the object could then be adjusted to best fit the data points while maintaining the symmetry requirement. This is an example of capturing design intent rather than simply recreating a model from raw data.

8.1.1.2 Cycle Remembering

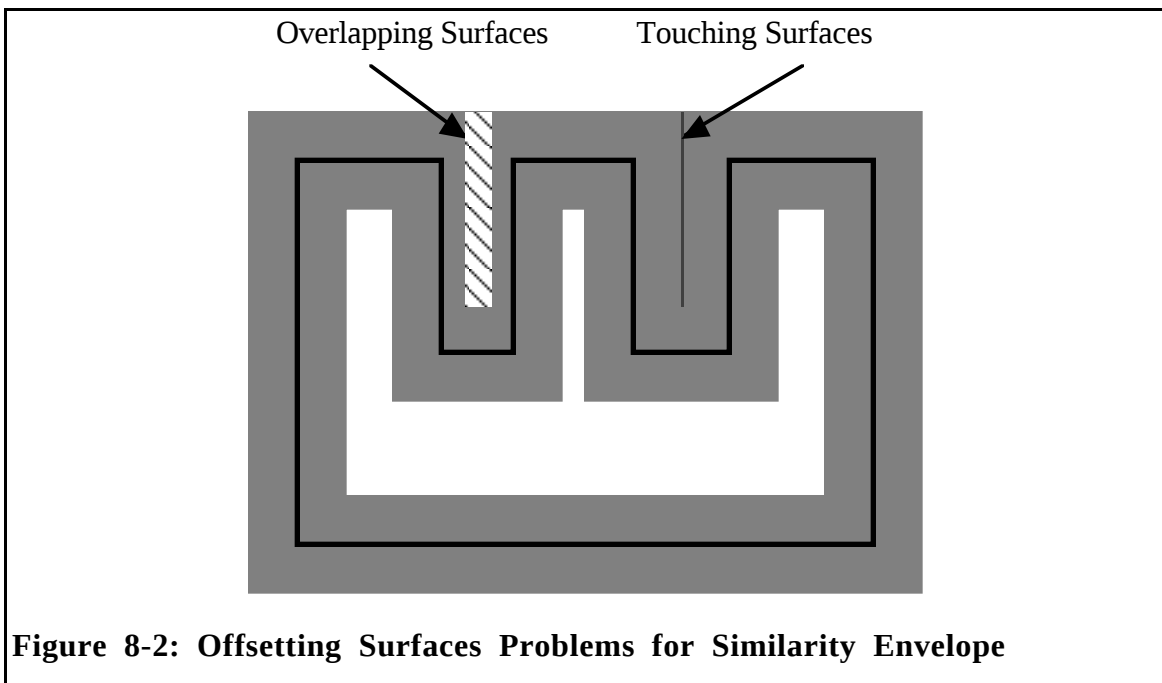
Finding shape features as described in the previous section might be semi-automated if the reconstructed CAD model had a method of comparing itself with the original CAD model that was used to create the physical prototype. In other words, only the changes made to the physical model would be registered and modified and the rest of the model would revert back to the original CAD model. This would hopefully create a more simple CAD model as well as reduce time needed to extract shape features.

There are two problems that must be confronted in order to remember cycle iterations. The first is how to align the new model to the old. Depending on how much the physical model is modified this problem could be as simple as having the user define three common points if there are not significant changes. If the digitized model is significantly different from the original one then the solution may not be so easy. Regardless of the solution to this problem it will need user interaction and will be difficult to automate.

The other problem is the comparison to identify which parts have been modified. A possible solution to this is to create offsetting surfaces within a tolerance of the original model and build a “similarity envelope” where the two models can be compared and differences can be identified. This idea is shown as a two dimensional example in Figure 8-1.



Unfortunately, offsetting surfaces of an object is well known as a difficult problem. There are several problems. Two of which, overlapping surfaces and touching surfaces, are shown in Figure 8-2. These are similar problems that the rapid prototyping standard CAD file, .STL, has as well. The first is overlapping surfaces and the second defines two surfaces in the same location with normals in opposite directions.



Inventing solutions to this problem is a complete research topic in itself. However, one such solution is to take advantage of the fact that the raw data of the digitized object comes as a discrete (voxel) representation. In order to build a “similarity envelope”, the original CAD model could be discretized itself. Then, using the erosion and dilation techniques described in chapter 6 on page 64, a big model and a small model could be created and the subtraction of the two yields a discrete “similarity envelope.” The problems associated with offsetting surfaces is solved because this discrete representation only deals with whether the part exists or does not exist in a certain location in space. The erosion and dilation algorithms take care of it.

8.1.1.3 Carving and Shaping Tools

The ability to intuitively carve and shape complex freeform surfaces in CAD models is still limited at this time. However, in order to make the design cycle as versatile as possible, a method for carving and shaping should be implemented. Literature shows that there is already research in this area with groups both in the United States and abroad [Salisbury],[Murakami].

One may argue that the physical model should be the only method of input to the design cycle for freeform shapes. This idea is flawed because translation between the two mediums is still the most time consuming task and if little modifications can be made easily in the CAD model then that is where it should be done. The design cycle’s main contribution is to allow designers freedom in their work and not constrain them to a certain method.

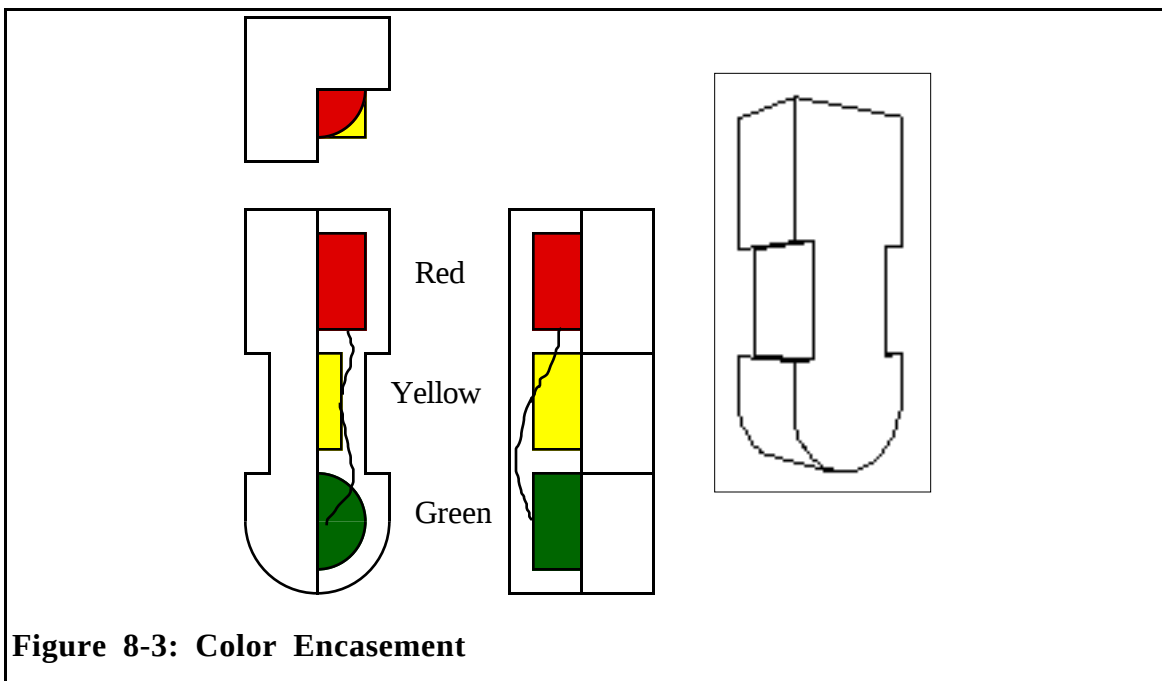
8.1.2 Wax 3D Printer

As described in chapter 3, work has been done on a drop on demand wax 3D printer using a Tektronics color dye sublimation printhead. In order to explore the speed of the design cycle a working machine should be finished. 3D printing has an incredible advantage over other types of rapid concept modeling techniques in the category of speed because the majority of the material of the part is put down in bulk and bound together. For the wax printer, it may only have to print half to a third of the total volume of the object. Other rapid concept modeling methods being developed right now must build objects one entire element at a time meaning that all the material of the part must be deposited serially. 3D printing will always be two to three times faster than other competitors.

8.1.3 Color Printing

The Tektronics printhead was developed for color printing paper documents and the output of these printers is quite remarkable. Other than just printing objects, there are applications for being able to print with multiple colors. Therefore, when the wax 3D printer is developed, color capability should also be included.

One application for multiple color printing involves the design cycle and another is in the medical field. Being able to print with multiple colors would allow a designer to create an object with internal limitations. An example would be a toy that had a battery pack, transmitter, servo, and wires etc. that were contained on the inside of the part. A blocked out encasement for the parts could be made and the whole object could be printed in different colors as shown in Figure 8-3. The designer can then carve the object and know what depth is permissible.



Physicians at the Brigham and Women's Hospital expressed interest in color 3D printing as well. As described also in the applications chapter on page 88, medical visualization using high-end computer graphics is an important tool for doctors. Computers allow them to see and diagnose problems that were previously impossible. However, just like engineers, doctors sometimes need physical models to help them understand a problem.

Color printing in particular, gives the ability for models of a patients body to be created which highlight certain items. For example, a surgeon might want to have a local model of their patients tumor. The tumor and surrounding nerves, bone, and fascia would all be different colors. This gives the surgeon the ability to cut, feel, explore, and see the situation physically as well as with computer graphics before the patient is opened up.

Orthopedic surgeons commented that even with advanced computer graphics, it is difficult to visualize a severe bone fracture or joint rupture. They often don't find out what they need to do until the patient is on the operating table. Using color again to highlight bone, a model could be made and the surgeon could understand a complex fracture beforehand.

8.1.4 Automated Digitizer

Along with building a wax printer, the digitizing process could also be automated. This will help in reducing the translation time between physical and computer model. As a prototype digitizing system, a handheld digital scanner could be mounted onto a CNC milling machine and connected to a PC in order to collect the data. However, this is only a small step above the hand milling and scanning done thus far. Since the digitizing process is repetitive and simple, a new machine that can mill and scan could also be designed and built.

8.1.5 Export for Manufacture

One point that was never formally addressed was that at some point a finished design must leave the cycle and be manufactured either as a single piece or in mass production. The design cycle is a process for designing geometry. Since there is only one material used for the prototyping in this research, it is not an actual manufacturing method.

3D printing is a versatile manufacturing method. It is well established as a good process for ceramic casting shells and research is progressing in tooling for injection molding. If either of these are the method for manufacture of the final designed part then the work is there already exists an avenue to leave the design cycle and produce parts. However, if another method is required, then there are limitations. However, by implementing the suggestions in section 8.1.1.1 Shape Features the CAD model can be exported to virtually any other manufacturing method.

8.2 Conclusions

In this work a complete design cycle has been built where a designer has the ability to manipulate either electronic or physical models and can translate between the two. All the problems associated with completing this design cycle have been solved. Simple as well as complex examples have been demonstrated.

In Chapter 1, a question was raised whether or not this design cycle was useful. Hopefully, this thesis has answered that question in the affirmative. Designers often work within and are limited to the capabilities of their available tools. This research has pushed the envelope of those design limitations concerning complex 3D shape design. There is still much work to be done to make the design cycle a fully integrated and fluid design system. Nevertheless, the design cycle concept has the possibility of becoming a contribution as a powerful new design tool.

Appendix 1 – TWIN File Format

Example of TWIN file format for a unit cube. Comments are not permitted in an actual file.

```
#TWIN 1                                /*file version identifier*/
8                                      /* There are 8 vertices */
0.000000 0.000000 0.000000
1.000000 0.000000 0.000000
0.000000 1.000000 0.000000
0.000000 0.000000 1.000000          /* 3D coordinates */
1.000000 0.000000 1.000000
0.000000 1.000000 1.000000
1.000000 1.000000 0.000000
1.000000 1.000000 1.000000
12                                     /* There are 12 edges */
5 2
5 4                                     /* This edge begins at vertex 5 and ends at 4 */
4 1
2 1
7 2
7 8
8 5
7 3
6 3
8 6
6 4
3 1
6                                     /* There are 6 faces */
1                                     /* This face has surface ID = 1 */
-31044                                /* This is the data stored in prim for this face */
1 0                                   /* There is 1 loop in this face */
4 -1 2 3 -4                           /* There are 4 edges in this loop */
2
4
1 0
4 1 -5 6 7                             /* Edge 5 is in the negative direction */
3
0
1 0                                     /* This face is in group # 0 */
4 -6 8 -9 -10
4
4598
1 0
4 -3 -11 9 12
5
-1
1 0
4 -7 10 11 -2
6
0
1 0
4 -8 5 4 -12
```

Appendix 2 – Company Contact Information

Rapid Prototyping

Cubital
1307F Allen Drive
Troy, Michigan, 48083
810-585-7880
Fax 810-585-7884

DTM Corporation
1611 Headway Circle, Bldg. 2
Austin, TX 78754
512-339-2922
Fax 512-832-6753

Sanders Prototype, Inc.
P. O. Box 540
Wilton, NH 03086
603-654-5100
FAX 603-654-2616

Stratasys, Inc.
14950 Martin Drive
Eden Prairie, MN 55344-2020
612-937-3000
Fax 612-937-0070

3D Printing Laboratory
MIT
77 Massachusetts Avenue
35-136
Cambridge, MA 02139
617-258-5602
Fax 617-0209

3D SYSTEMS
26081 Avenue Hall
Valencia, CA 91355
805-295-5600
Fax 805-257-1200

Materials

Koster Keunen Inc.
1021 Echo Lake Rd.
P.O. Bos 69
Watertown, CT 06795
203-945-3333
Fax 203-945-0330

Potters Industries, Inc.
2380 West 3rd St.
Cleveland, OH 44113

Reverse Engineering

Capture Geometry Inside
7665 Commerce Way, #80
Eden Prairie, MN 55344
612-937-2005
Fax 612-937-3018

Digibotics, Inc.
2800 Longhorn Blvd.
Suite 102
Austin, TX 78758
512-832-9040
Fax 512-832-1163

Laser Design Inc
9401 James Avenue South
Suite 162
Minneapolis, MN 55431

CAD

Autodessys, Inc.
2011 Riverside Drive
Columbus, OH 43221
614-488-8838
Fax 614-488-0848

Imageware
313 N. First Street
Ann Arbor, MI 48103
313-994-7300
Fax 313-994-7303

Parametric Technology Corporation
128 Technology Drive
Waltham, MA 02154
617-398-5000
Fax 617-398-5650

Bibliography

- 3D Systems, Inc. (1990). "StereoLithography Interface Specification." , 3D Systems, Inc., Valencia, CA.
- Aldus (1992). "Tiff Revision 6.0." , Seattle, WA.
- Allen, S., Dutta. (1994 Submitted). "Determination & Evaluation of Support Structures in Layered Manufacutring." Journal of Design & Manufacutring.
- Ashley, S. (1995). "Rapid prototyping is coming of age." Mechanical Engineering, 63-68.
- Ashley, S. (1996). "Rapid concept modelers." Mechanical Engineering, 64-66.
- Autodessys, Inc. (1995). "FormZ." , Columbus, OH.
- Baker. (1988). "Building, Visualizing, and Computing on Surfaces of Evolution." IEEE Computer Graphics & Applications(July), 31-41.
- Becher, C. T. (1996). "Adaptation of the Three Dimensional Printing Process to a Drop-On-Demand Mode," No. 169789, Technischen Hochschule Aachen / Massachusetts Institute of Technology, Aachen / Cambridge.
- Ben-Ezra, B., Pomerantz, Sava, Hasharon, Shamir, Raanana. (1992). "Method and apparatus for volumetric digitazation of 3-Dimensionasal objects." United States Patent, Cubital Ltd., Herzlia, Israel, USA.
- Blake, I. "3D position, attitude and shape input using video tracking of hands and lips." SIGGRAPH 94, Orlando, Florida, 185-192.
- Celniker, G. (1990). "ShapeWright," , Massachusetts Institute of Technology, Cambridge, MA.
- Celniker, G., Gossard. (1991). "Deformable Curve and Surface Finite-Elements for Free-Form Shape Design." Computer Graphics, 25(4), 257-266.
- Crandall, S., Karnopp, Kurtz, Pridmore-Brown. (1982). Dynamics of Mechanical and Electromechanical Systems, Krieger Publishing Company, Malabar, Florida.
- Cromwell, G. W. (1994). Candlemaking Simplified, Walnut Hill, Bristol, PA.
- Editor. (1995). "Designing Implants with a Custom Fit." Mechanical Engineering, 24.
- Fay, J. A. (1994). Introduction to Fluid Mechanics, MIT Press, Cambridge, Massachusetts.
- Heller, D. (1992). Motif Programming Manual, O'Reilly & Associates, Inc., Sebastopol, CA.
- Hoppe, H., DeRose, Duchamp, Jin, McDonald, Stuetzle. (1991). "Surface Reconstruction from Unorganized Points." 91-12-03, Universtiy of Washington, Seattle, WA.

- Hoppe, H., DeRose, Duchamp, Jin, McDonald, Stuetzle. (1993). "Mesh Optimization." 93-01-01, University of Washington, Seattle, WA.
- Hoppe, H., DeRose, Duchamp, Jin, McDonald, Stuetzle. (1994). "Piecewise Smooth Surface Reconstruction." 94-01-01, University of Washington, Seattle, WA.
- Imageware. (1994). "Surfacer." , Ann Arbor, MI.
- Jaikumar, R. (1988). "From Filing and Fitting to Flexible Manufacturing: A Study in the Evolution of Process Control." , Harvard Business School, 64.
- Jee, H. (1996). "Computer-Aided Design of Surface Macro-Textures for Three Dimensional Printing," Doctor of Philosophy, Massachusetts Institute of Technology, Cambridge, MA.
- Kalpakkjian, S. (1995). Manufacturing Engineering and Technology, Addison Wesley, Reading, Massachusetts.
- Kass, M., Witkin, Terzopoulos. (1988). "Snakes: Active Contour Models." International Journal of Computer Vision, 321-331.
- Kikinis, R., Jolesz, Gerig, Sandor, Cline, Lorensen, Halle, Benton. "3D Morphometric and Morphologic Information Derived From Clinical Brain MR Images." NATO Advanced Wordshop on 3D in Medical Imaging.
- Kobayashi, H., Aoki, Kudou. (1995). "Development of Microslicer Implementation of 3 Dimentional Internal Structure Microscope." Journal of the Japan Society for Precision Engineering, 61(1).
- Kudoh, K., Higuchi, Yokota, Satoh. (1994). "Development of Device for 3D Image Construction from Biological Sample." Japan Journal of Mechanical Engineering, 32, 323.
- Laser Design, I. (1994). "3D Laser Digitizing Systems, Software, & Services." , Laser Design Inc., Minneapolis, MN.
- Loop, C. (1987). "Smooth subdivision surfaces based on triangles," Master's thesis, University of Utah, Salt Lake City.
- Lorensen, W. E., Cline. (1987). "Marching Cubes: A High Resolution 3D Surface Construction Algorithm." SIGGRAPH '87, 21(4), 163-169.
- Markowsky, G., Wesley. (1980). "Fleshing Out Wire Frames." IBM Journal of Research and Development, 24(5), 582-597.
- Markowsky, G., Wesley. (1986). "Generation of Solid Models from Two-Dimensional and Three-Dimensional Data." Solid Modelling by Computer: from Theory to Application Plenum, M. Picket, ed., 23-51.
- Martinez, C. D. (1994). "Inside 3-D Modeling." MacWorld, 86-92.
- McInerney, T., Terzopoulos D. (1994). "A Dynamic finite Element Surface Model for Segmentation and Tracking in Multidimensional Mediacal Images with Aplication to

- Cadiac 4D Image Analysis.” , University of Toronto, Department of Computer Science, Toronto, ON.
- Murakami, T., Nakajima. “Direct and Intuitive Input Device for 3-D Shape Deformation.” Human Factors in Computing Systems, Boston, MA, 465-470.
- Nammour, D. E. (1995). “Fabrication of Glass-Ceramic Components via Three Dimensional Printing,” , Massachusetts Institute of Technology, Cambridge, MA.
- Netter, F. H. (1993). Atlas of Human Anatomy, CIBA-GEIGY Corporation, Hong Kong.
- Paeth, A. W. “A Fast Algorithm for General Raster Rotation.” Graphics Interface '89, Canadian Information Processing Society, 77-81.
- Renze, K., Oliver. (1994). “Generalized Surface and volume Decimation for Unstructured Tessellated Domains.” , Iowa State University, Department of Mechanical Engineering, Ames, IA.
- Rothenberg, M. (1995). “Tektronix solid-ink printer redraws lines in color-output race.” MacWeek, 1,72.
- Sachs, E., Cima, Williams, Brancazio, Cornie. (1992). “Three Dimensional Printing: Rapid Tooling and Prototypes Directly from a CAD Model.” Journal of Engineering for Industry, 114(4), 481-488.
- Sakurai, H., Gossard. “Solid Model Input Through Orthographic Views.” SIGGRAPH '83, 243-252.
- Salisbury, K., Brock, Massie, Swarup, Zilles. “Haptic Rendering: Programming Touch Interaction with Virtual Objects.” ACM Symposium on Interactive 3D Graphics, Monterey, CA.
- Schildt, H. (1994). Teach Yourself C++, Osborne McGraw Hill, New York.
- Shimada, K., Gossard. “Computational Methods for Physically-based FE Mesh Generation.” , Tokyo, Japan.
- Sprow, E. E. (1992). “Rapid Prototyping.” Manufacturing Engineering, 58-64.
- Strang, G. (1994). “Wavelets.” American Scientist, 250-255.
- Stroustrup, B. (1991). The C++ Programming Language, Addison-Wesley, Reading, Massachusetts.
- Thompson, W., Owen, de st. Germain. (1995). “Feature-Based Reverse Engineering of Mechanical Parts.” , Computer Science Department, University of Utah.
- Tjalve, E. (1979). A Short Course in Industrial Design., Newnes-Butterworths, Boston.
- Wesley, M., Markowsky. (1981). “Fleshing Out Projections.” IBM Journal of Research and Development, 25(6), 934-954.
- Zeid, I. (1991). CAD/CAM Theory and Practice, McGraw-Hill, Inc., New York.