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

by

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B.S., Mechanical Engineering
Brigham Young University
April 1994

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

Master of Science
in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 1996

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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.

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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.

Sarah – These past two years have been amazing. Thank you for your persuasion, long-suffering, gentleness, meekness, kindness, and love unfeigned. Best friends, Always! 143

Professor Ely Sachs – Thank you for your constant guidance and advise, not only in research but in life's lessons, choices, and decisions. I have appreciated all that I have learned from you not only as an advisor and teacher but as a friend.

Professor David Gossard – Thank you for your encouragement, guidance, and in helping me to maintain perspective and keep moving.

Members of the MIT CADlab and 3D Printing lab – Thank you for filling this experience with wonderful camaraderie in both work and fun.

National Science Foundation – I acknowledge the NSF for their generous financial support.

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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.

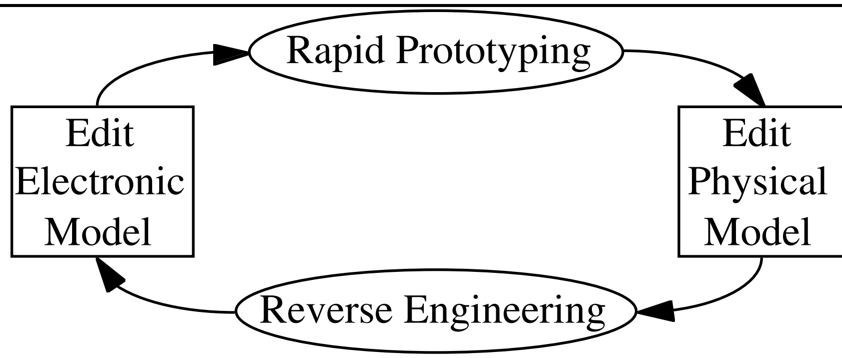

Figure 0-1: Design Cycle Concept

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.

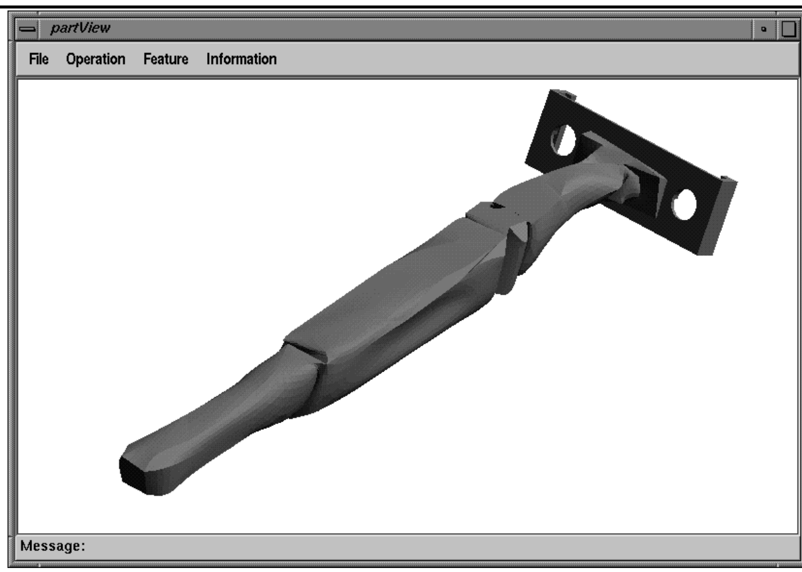

Figure 0-2: Complex Sculptured Razor Handle – Demonstration of the Design Cycle

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.

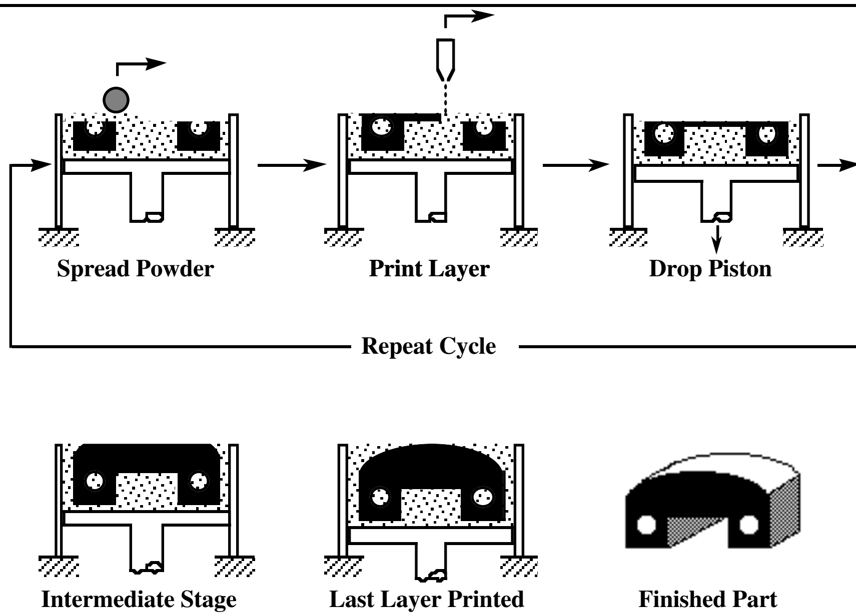

Figure 0-3: Three Dimensional Printing Sequence of Operations

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.

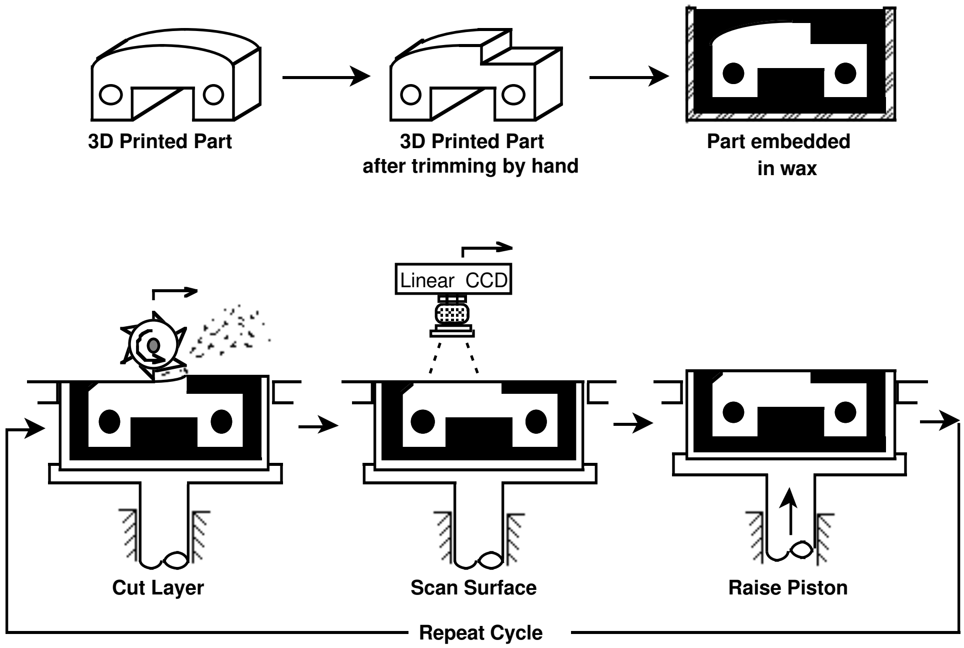

Figure 0-4: Layer by Layer Digitizing (Deconstruction)

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 posibility 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.

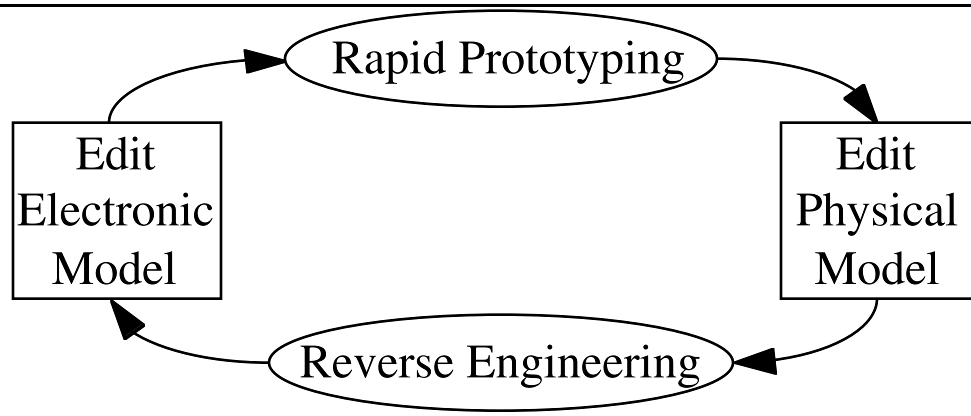

Figure 1-1: Design Cycle Concept

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.

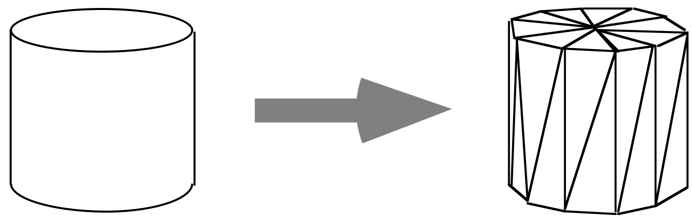

Figure 2-1: Polygonalized Model from Solid Geometry (.STL)

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.

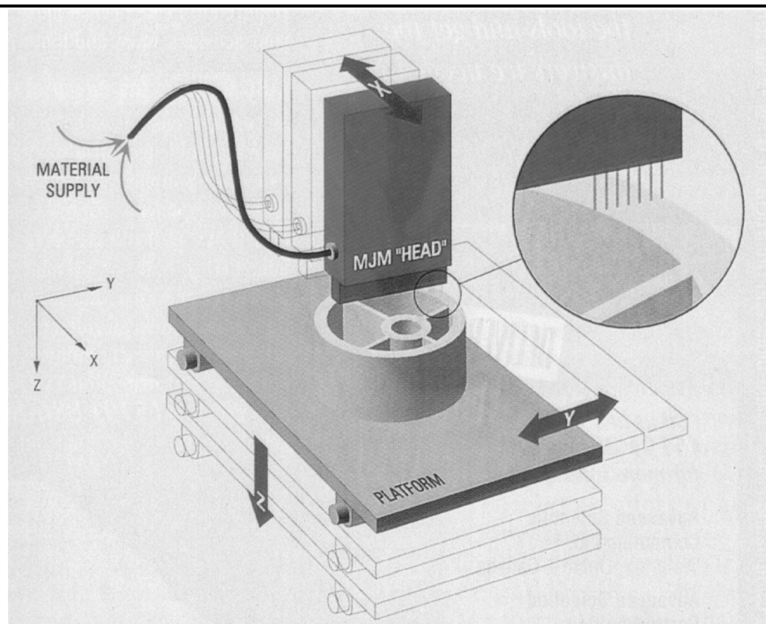

Figure 2-2: 3D Systems Rapid Concept Modeler

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.

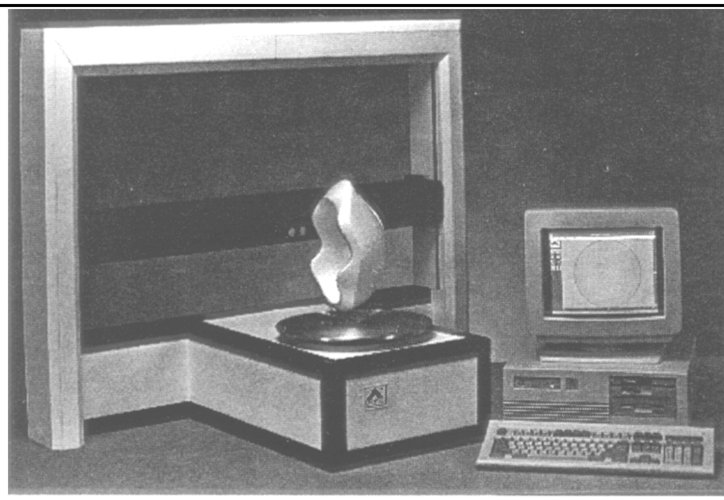

Figure 2-3: Digibotics Laser Scanner with Turntable

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.

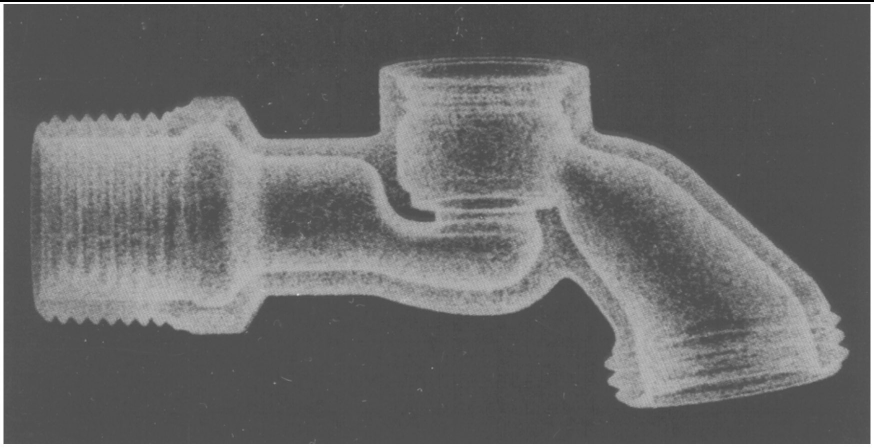

Figure 2-4: CGI Point Cloud Results of a Faucet with Internal Geometry

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 Surfacer, 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.

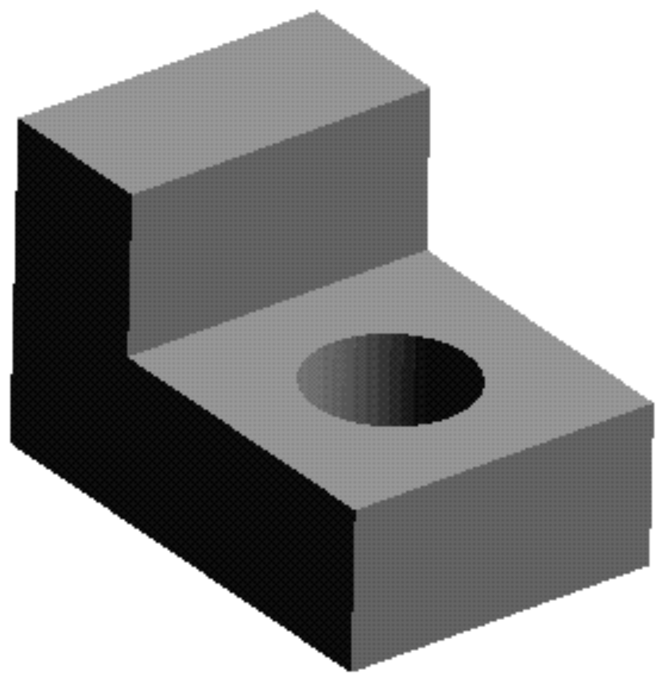

Figure 2-5: Demonstration Block Used for Testing Design Cycle

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.

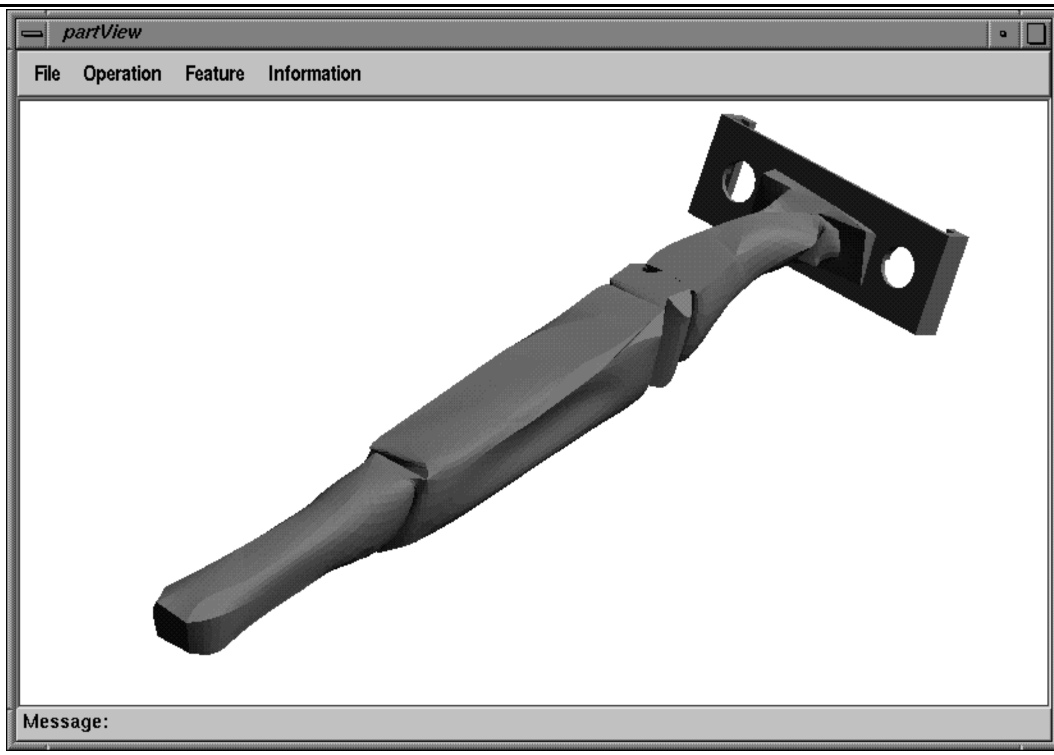

Figure 2-6: Complex Sculptured Razor Handle

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.

Chapter 3

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.

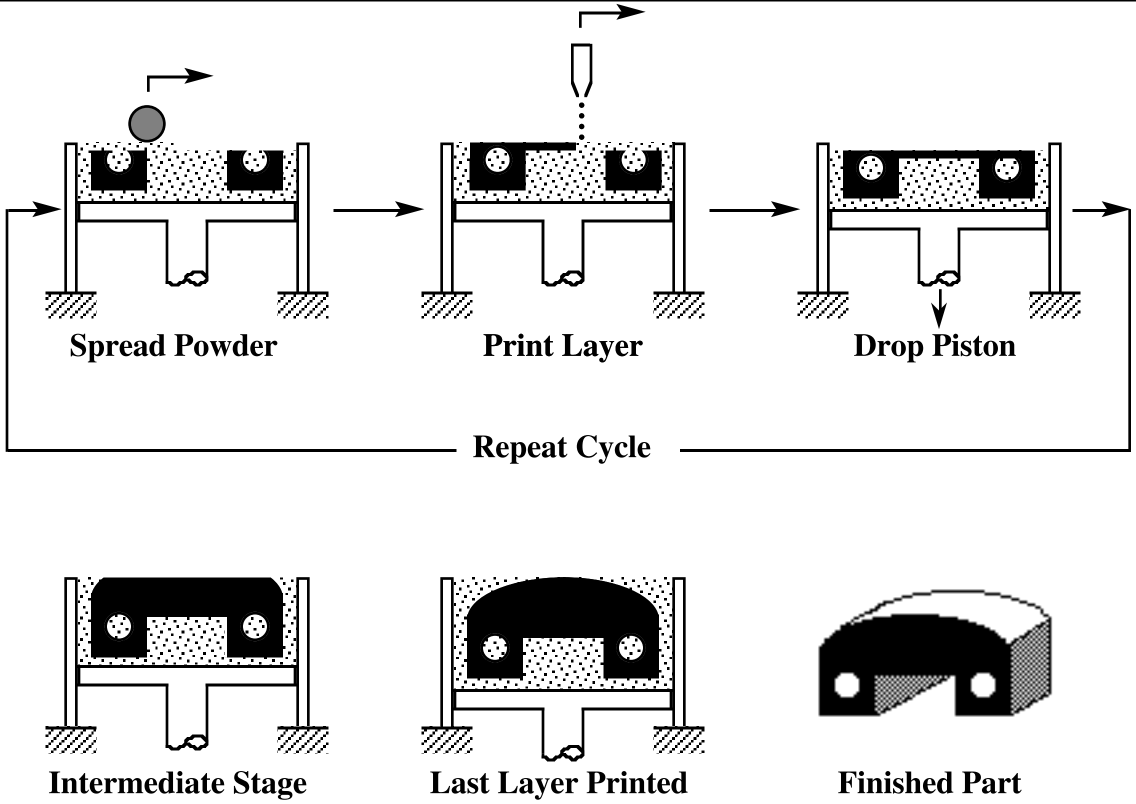

Figure 3-1: 3D Printing Sequence of Operations

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.

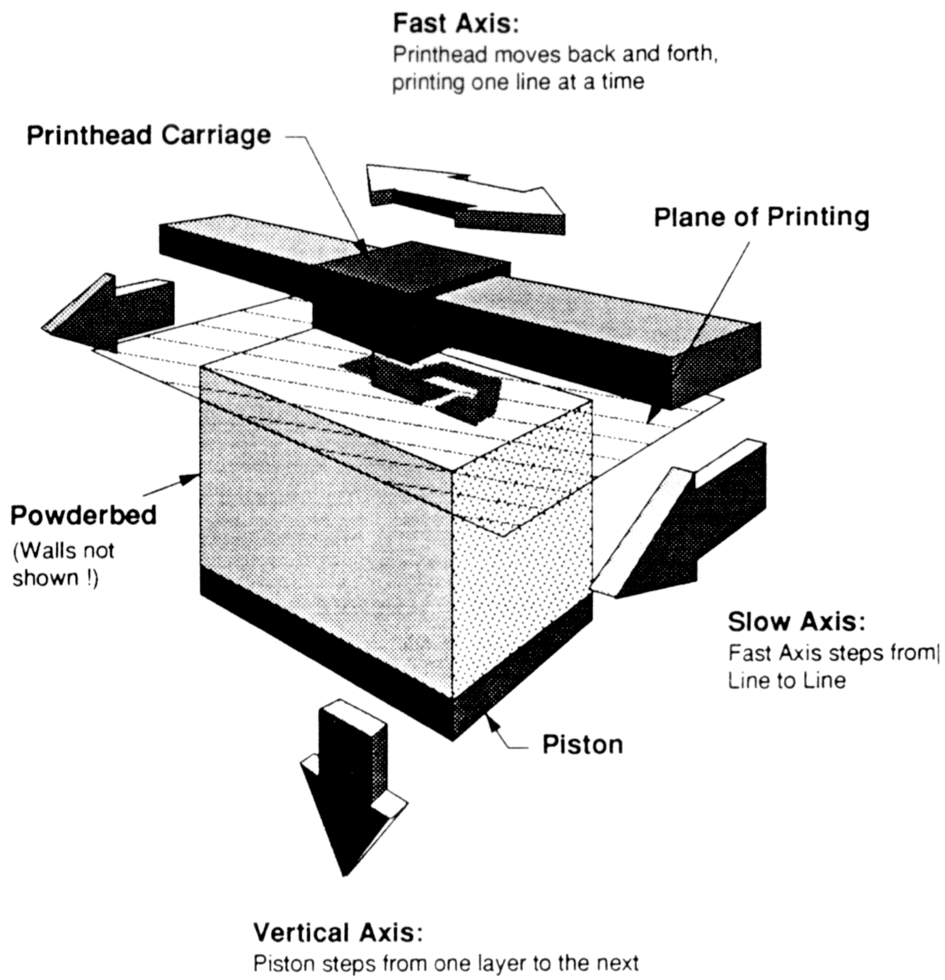

Figure 3-2: Perspective View of 3D Printing with Terminology Definitions

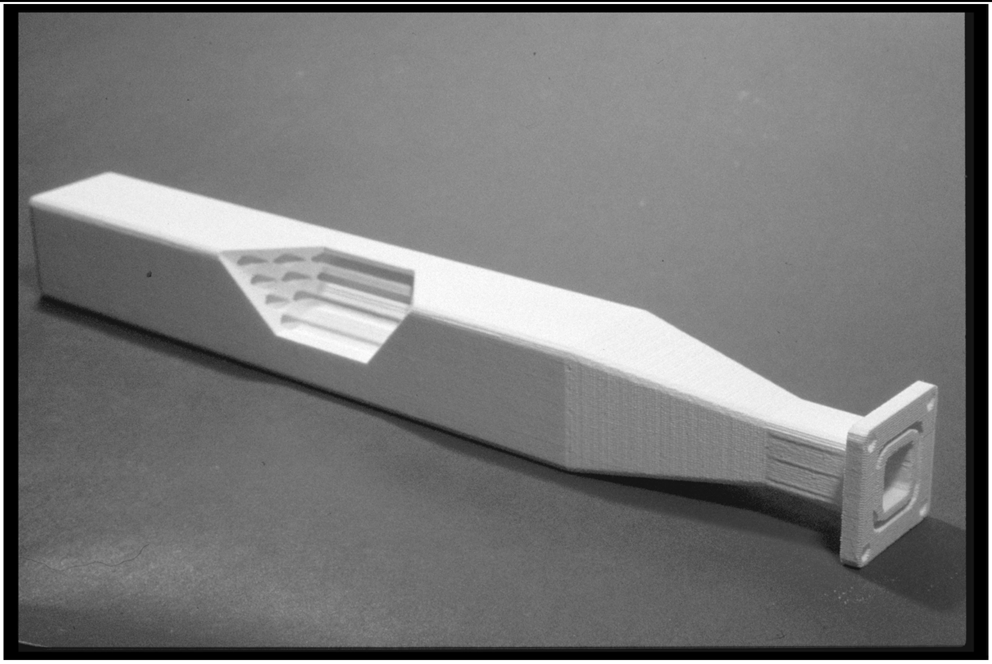

Figure 3-3: Filter Created by 3D Printing – Demonstrates Internal Geometry Capabilities

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.

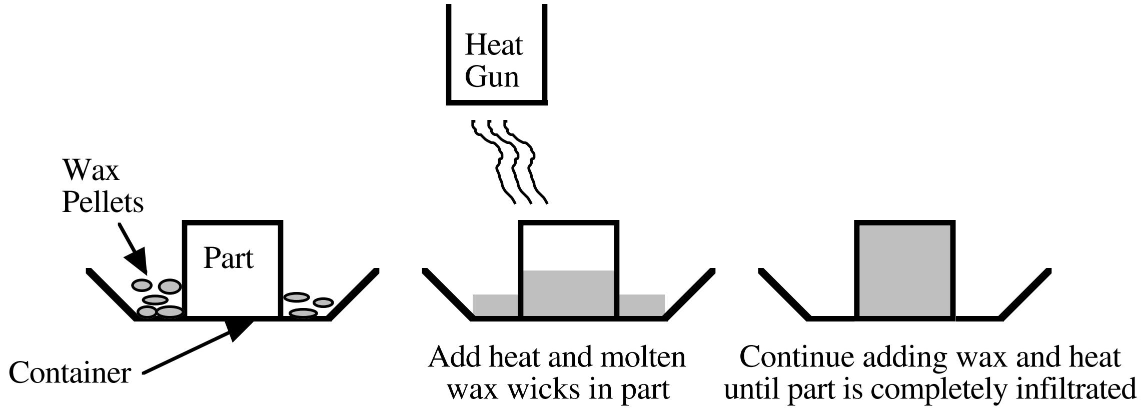

Figure 3-4: Infiltration Sequence of Operations

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.

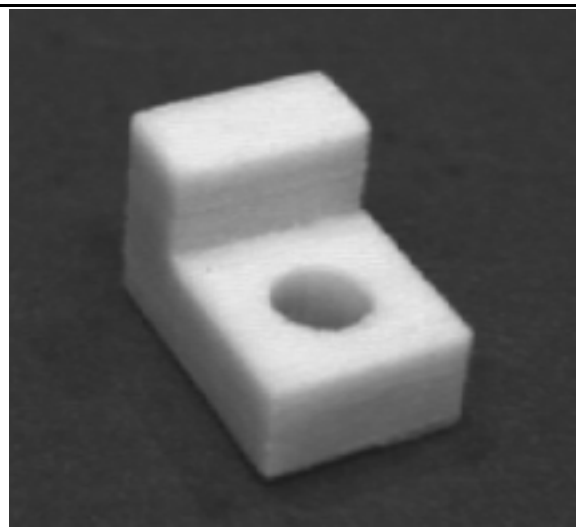

Figure 3-5: Glass Powder Block Made by 3D Printing with Bees Wax Infiltrant

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 Delecate 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.

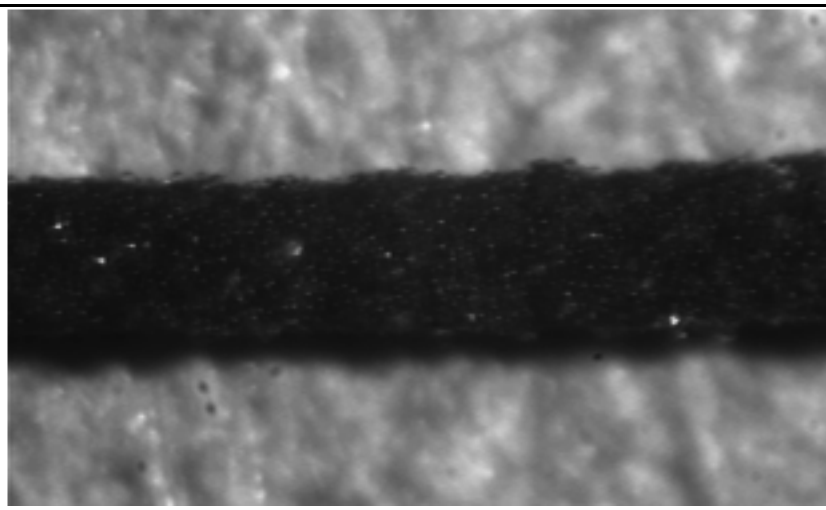

Figure 3-7: Printed Line of Black Wax and Spherical Glass Powder

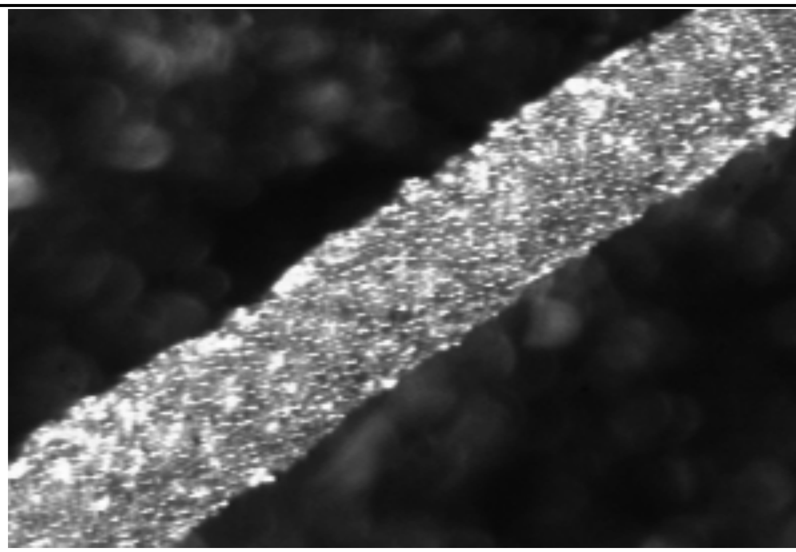

Figure 3-8: Printed Wax Line

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.

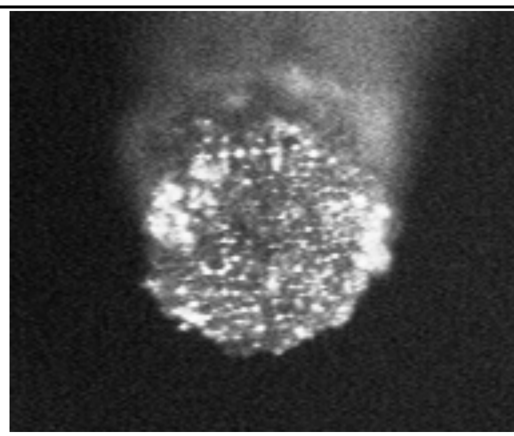

Figure 3-9: Printed Wax Line Cross-Section

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.

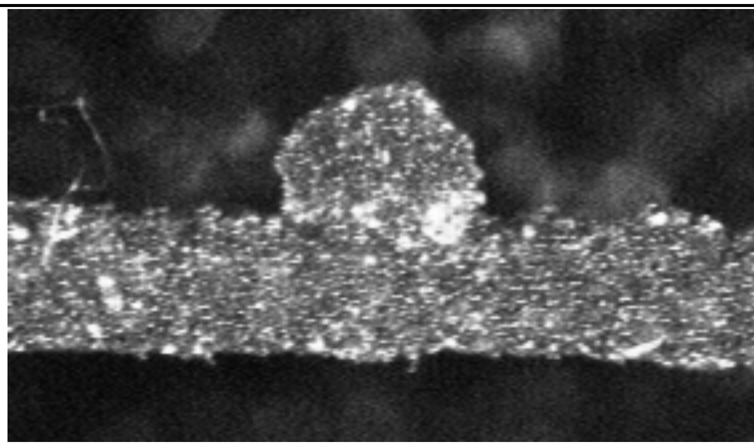

Figure 3-10: Printed Line with Cross Part

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.