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APPLICATION OF REVERSE ENGINEERING AND RAPID PROTOTYPING TO CASTING

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submitted in partial fulfillment of requirements for the degree

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at the

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APPLICATION OF REVERSE ENGINEERING AND RAPID PROTOTYPING TECHNIQUES TO CASTING

VENKAT DEEPAK KOLAR

ABSTRACT

The automotive industry has an increasing need for the remanufacturing of spare parts through reverse engineering. In this thesis we will review the techniques used in Fused Deposition Modeling system for the reverse engineering of vintage automotive parts. The objective of the project is to be able to generate part-to-CAD and CAD-to-part reconstruction of the original part for future usage. These newly created 3D models will be added to the 3D Part Database.

The integration of reverse engineering and rapid prototyping is being used for getting product to the market quickly by resolving a long-standing conflict between design and manufacturing.

Rapid prototyping (RP) technology has undoubtedly had a major impact on the manufacturing industry throughout the world. RP technology has developed as a result of the requirements of manufacturing industry. There are a number of application areas where RP has been used to good effect and one of these is Metal Casting. This thesis describes work carried out to investigate potential applications for metal casting, as well as an attempt to explore the limits of the technology. It will go on to discuss how the technology may be developed to better serve the requirements of the manufacturing industry.

TABLE OF CONTENTS

Page

NOMENCLATURE…….....viii

LIST OF TABLES.....ix

LIST OF FIGURES.....x

I INTRODUCTION …….…….....1

II REVERSE ENGINEERING.....4

2.1 Introduction…….……..4

2.2 Value Engineering Vs Reverse Engineering……..……...5

2.3 What Is Reverse Engineering?…..……5

2.4 Reason for Reverse Engineering……...……7

2.5 Reverse Engineering Process...…….…..……10

III RAPID PROTOTYPING AND MANUFACTURING…….……14

3.1 Introduction…….……14

3.2 What is Rapid Prototyping? …….……..……15

3.3 Applications of RP.....16

3.4 RP fundamentals……..……...18

3.5 Problems with STL File Format……...……..21

3.6 Development of RP Systems……..23

IV FUSED DEPOSITION MODELING…….....26

4.1 Company Profile ....….26

4.2 Fused Deposition Modeling System Hardware.....27

4.3 Fused Deposition Modeling Operation.....29

4.4 Products.....32

4.5 Advantages of FDM System.....32

4.6 Disadvantages of FDM System.....33

V LABORATORY FACILITY…….……...34

5.1 Experimental Setup.....34

5.2 Reverse Engineering Tools.....35

5.3 Procedure.....36

5.4 FDM and Sand Casting.....43

VI APPLICATION OF REVERSE ENGINEERING AND RAPID PROTOTYPING TO MANUFACTURING.....……...44

6.1 Rapid Prototyping and Manufacturing.....45

6.2 Application of Rapid Prototyping to Fabricate a Pattern.....46

6.3 Sand Casting Design.....47

6.4 Process Overview.....50

VII SUMMARY AND CONCLUSION.....53

7.1 Fused Deposition Modeling.....53

7.2 Conclusion.....54

REFERENCES.....56

NOMENCLATURE

CAD/CAM	Computer-Aided Design/Computer-Aided Manufacturing
RE	Reverse Engineering
RP	Rapid Prototyping
PTPD	Preliminary Technical Data Package
ABS	Acrylonitrile Butadene Styrene
CTDP	Complete Technical Data Package
TDP	Technical Data Package
UV	Ultra Violet
SLS	Selective Laser Sintering
SLA	Stereolithography Apparatus
FDM	Fused Deposition Modeling
LOM	Laminated Object Manufacturing
MM	Multi-Material
MEMS	Micro Electro Mechanical Systems
μSL	Micro-stereolithography
RT	Rapid Tooling
RTV	Room Temperature Vulcanized

LIST OF TABLES

Table **Page**

TABLE 1: Dimension Tolerance Table 49

LIST OF FIGURES

Figure **Page**

Figure 1: Flowchart showing basic transformation phases of reverse engineering...10

Figure 2: Generic Rapid Prototyping process.....15

Figure 3: Rapid Prototyping Wheel.....17

Figure 4: The Rapid Prototyping Cycle.....19

Figure 5: The Extrusion Head.....28

Figure 6: An STL file as viewed by Catalyst.....29

Figure 7: Sliced Model.....31

Figure 8: RevWorks Toolbar.....35

Figure 9: Setup at the Component Evalution and Prototyping Lab at CSU.....37

Figure 10: Datum setup from the pull down menu of RevWORKS.....38

Figure 11: Menu for Datum selection.....39

Figure 12: Microscribe G2 Digitizer.....40

Figure 13: Stratasys Dimension BST 3D Printer.....41

Figure 14: Comparison of sample part and ABS pattern.....47

Figure 15: Cope and Drag.....50

Figure 16: Reverse Engineered Part just out of the mould.....51

Figure 17: Comparison of the Sample Part and RE.... Part.....52

Figure 18: The FDM-ABS pattern as fabricated.....54

CHAPTER I

INTRODUCTION

This Thesis describes a complete prototyping process using the Reverse Engineering techniques. The geometry of a mechanical component is captured using digitizing arm and Reverse Engineering (RE) software. The Rapid prototyping process used is Fused Deposition Modeling (FDM) system. It also describes the step-by-step procedure for making the prototype (ABS Pattern) as well as the hardware and software used for making the prototype model (Aluminium Casting).

Reverse engineering is the opposite of forward engineering. It takes an existing product, and creates a CAD model, for modification or reproduction to the design aspect of the product. It can also be defined as the process or duplicating an existing component by capturing the components physical dimensions. Reverse engineering is usually undertaken in order to redesign the system for better maintainability or to produce a copy of a system without access to the design from which it was originally produced.

In many cases sufficient or current technical data is missing, inaccurate, or outdated. Often unavailable technical data needed to maintain and repair equipment was never furnished or purchased. Examples of such situations include hand made prototypes,

reproduction of old engineering objects and sculptured bodies found in medical and dental applications. In order to facilitate computer-aided manufacturing (CAM) operations of these physical models, it’s essential to establish their CAD models. RE is the quickest way to get the data into any computer system. Technical data is critical to the smooth and continuous operation of any production or manufacturing facility.

There has been a mandatory need for 3D reconstruction of objects by the manufacturing industry, medical industry, military branches and research facilities. Manufacturing industry utilizes reverse engineering for its fast rapid prototyping abilities and accuracy associated with the production of new parts. This fast prototyping is done through the use of CAD model designs for inspection purposes.

One of our laboratory's current focuses is reverse engineering or 3D reconstruction of objects using the current Reverse Engineering system. The goal of reverse engineering an object is to successfully generate a 3D CAD model of an object that can be used for future modeling of parts where there exists no CAD model. We want to generate clean, smooth 3D models, which are free of noise and holes.

An ABS model (pattern) is created for the final casting to be made in Aluminium. This requires a strong, robust image acquisition system that can acquire data with a high level of accuracy in a sufficient time frame. The output is transformed data that is represented as 3D reconstructions

This is one of the general examples of what is more precisely known by its practitioners as "reverse engineering" (RE). The RE business has to continually evolve to keep up with the changes in electronics and design, and it has become a discipline in itself created by the needs of a diverse customer base.

Reverse engineering is not a reactive tool to use on an old problem but a proactive methodology to a present challenge. This challenge is to maintain and/or improve today's manufacturing capabilities efficiently and effectively using yesterday's machines before tomorrow comes.

CHAPTER II

REVERSE ENGINEERING

2.1 Introduction

Reverse engineering (RE) is the science of taking the existing physical model and reproducing its surface geometry in three-dimensional (3D) data file on a computer-aided (CAD) system. Reverse engineering is the general process of analyzing a technology specifically to ascertain how it was designed or how it operates. This kind of inquiry engages individuals in a constructive learning process about the operation of systems and products. RE as a method is not confined to any particular purpose, but is often an important part of the scientific method and technological development. The process of taking something apart and revealing the way in which it works is often an effective way to learn how to build a technology or make improvements to it.

Reverse engineering is the process of generating a Computer Aided Design (CAD) model from an existing part. It enables the reconstruction of an object by capturing the components physical dimension and geometrical features. It is a converse product design approach where the designer begins with the product and works through

the design process in an opposite sequence to arrive at product specifications such as dimensions and form. This enables the designer to mentally simulate design ideas that occur during the design of the original product.

2.2 Value Engineering Vs Reverse Engineering

Value engineering refers to the creation of an improved system or product to the one originally analyzed. While there is often overlap between the methods of value engineering and reverse engineering, the goal of reverse engineering itself is the improved documentation of how the original product works by uncovering the underlying design. The working product that results from a reverse engineering effort is more like a duplicate of the original system, without necessarily adding modifications or improvements to the original design.

2.3 What Is Reverse Engineering?

Engineering is the profession involved in designing, manufacturing, constructing, and maintaining of products, systems, and structures. At a higher level, there are two types of engineering: forward engineering and reverse engineering.

The most traditional method of the development of a technology is referred to as "forward engineering." In the construction of a technology, manufacturers develop a product by implementing engineering concepts and abstractions. By contrast, reverse engineering begins with final product, and works backward to recreate the engineering concepts by analyzing the design of the system and the interrelationships of its

components. Forward engineering is the traditional process of moving from high-level abstractions and logical designs to the physical implementation of a system. In some situations, there may be a physical part without any technical details, such as drawings, bills-of-material, or without engineering data, such as thermal and electrical properties.

The process of duplicating an existing component, subassembly, or product, without the aid of drawings, documentation, or computer model is known as reverse engineering.

Reverse engineering can be viewed as the process of analyzing a system to:

1. Identify the system's components and their interrelationships
2. Create representations of the system in another form or a higher level of abstraction
3. Create the physical representation of that system

Reverse engineering is very common in such diverse fields as automotive, mechanical designs, consumer products, software engineering, entertainment, microchips, chemicals, and electronics. For example, when a new machine comes to market, competing manufacturers may buy one machine and disassemble it to learn how it was built and how it works. A chemical company may use reverse engineering to defeat a patent on a competitor's manufacturing process. In civil engineering, bridge and building designs are copied from past successes so there will be less chance of catastrophic failure. In software engineering, good source code is often a variation of other good source code.

2.4 Reason for Reverse Engineering

In some situations, designers give a shape to their ideas by using clay, plaster, wood, or foam rubber, but a CAD model is needed to enable the manufacturing of the part. As products become more organic in shape, designing in CAD may be challenging or impossible. There is no guarantee that the CAD model will be acceptably close to the sculpted model. Reverse engineering provides a solution to this problem because the physical model is the source of information for the CAD model. This is also referred to as the part-to-CAD process.

Another reason for reverse engineering is to compress product development times. In the intensely competitive global market, manufacturers are constantly seeking new ways to shorten lead-times to market a new product. Rapid product development (RPD) refers to recently developed technologies and techniques that assist manufacturers and designers in meeting the demands of reduced product development time. For example, injection-molding companies must drastically reduce the tool and die development times. By using reverse engineering, a three-dimensional product or model can be quickly captured in digital form, re-modeled, and exported for rapid prototyping/tooling or rapid manufacturing.

While not many manufactures have considered using reverse engineering in the past, since it was perceived as a form of patent or design infringement, many are now being forced to look anew at this technique. There are many individual reasons for this change of heart, but by far the vast majority find that when they have lost suppliers for critical spare parts, reverse engineering may be the only alternative. If a part has a simple substitute, then there is no real long-term problem. It is often when a manufacturer is face

with long-term issues that Reverse Engineering becomes a viable alternative to having no future parts to maintain a production capability

Following are reasons for reverse engineering a part or product:

1. The original manufacturer of a product no longer produces a product
2. There is inadequate documentation of the original design
3. The original manufacturer no longer exists, but a customer needs the product
4. The original design documentation has been lost or never existed
5. Some bad features of a product need to be designed out. For example, excessive wear might indicate where a product should be improved
6. To strengthen the good features of a product based on long-term usage of the product
7. To analyze the good and bad features of competitors' product
8. To explore new avenues to improve product performance and features
9. To gain competitive benchmarking methods to understand competitor's products and develop better products
10. The original CAD model is not sufficient to support modifications or current manufacturing methods
11. The original supplier is unable or unwilling to provide additional parts
12. The original equipment manufacturers are either unwilling or unable to supply replacement parts, or demand inflated costs for sole-source parts

13. To update obsolete materials or antiquated manufacturing processes with more current, less-expensive technologies

Reverse engineering enables the duplication of an existing part by capturing the component's physical dimensions, features, and material properties. Before attempting reverse engineering, a well-planned life-cycle analysis and cost/benefit analysis should be conducted to justify the reverse engineering projects. Reverse engineering is typically cost effective only if the items to be reverse engineered reflect a high investment or will be reproduced in large quantities. The desired goal is always a product or component of higher efficiency or quality for a lower cost. Reverse engineering of a part may be attempted even if it is not cost effective, if the part is absolutely required and is mission-critical to a system.

It can be said that reverse engineering begins with the product and works through the design process in the opposite direction to arrive at a product definition statement (PDS). In doing so, it uncovers as much information as possible about the design ideas that were used to produce a particular product.

Since the reverse engineering process can be time-consuming and expensive, reverse engineers generally consider whether the financial risk of such an endeavor is preferable to purchasing or licensing the information from the original manufacturer, if possible.

2.5 Reverse Engineering Process

Generally speaking, reverse engineering is a series of four independent stages, each stage building on the findings of the previous stage preceded by a prescreening process. The whole process progresses linearly with time as shown in Figure1 [1]. It is charted on the flow diagrams which visually illustrate each step of each stage.

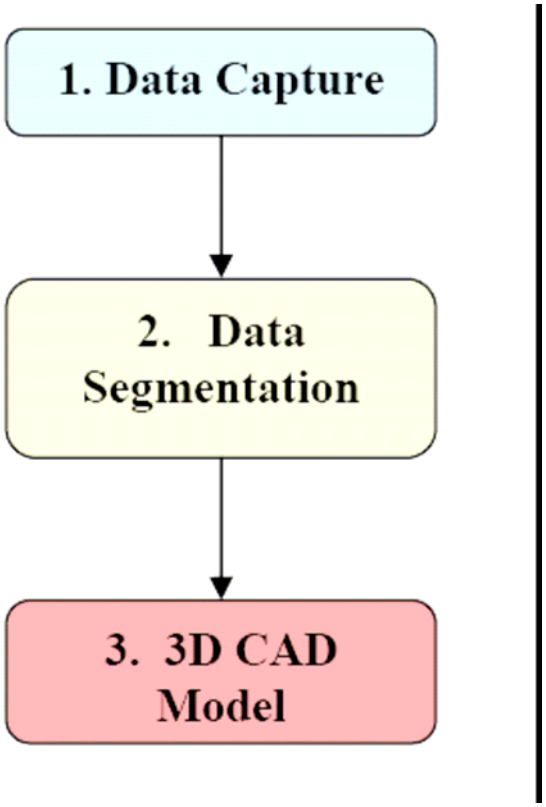


Figure 1 Flowchart showing basic transformation phases of reverse engineering

In order to reverse engineer a product or component of a system, engineers and researchers generally follow the following four-stage process:

- Stage 1: Evaluation and Verification
- Stage 2: Technical Data Generation
- Stage 3: Design Verification

- Stage 4: Project Implementation

2.5.1 Stage 1: Evaluation and Verification

The primary steps in Stage 1 are as follows:

- Visual and dimensional inspection
- Discrepancy review versus available data
- Failure analysis
- Quality evaluation report
- Stage 1 report
- Go/no-go decision

In the first stage in the process, sometimes called "prescreening," reverse engineers determine the candidate product for their project. Potential candidates for such a project include singular items, parts, components, units, subassemblies, some of which may contain many smaller parts sold as a single entity [1].

The visual and dimensional inspections constitute the first task conducted in stage 1. The visual inspection is simply a review of the overall condition of the part in terms of reproducibility, quality, and its present state of deterioration or wear. The available data is reviewed for completeness while the data adequacy is detailed. The stage 1 report contains the data necessary for project leader to recommend a decision to go onto stage 2 or to justify the decision to stop the project at the conclusion of stage 1 on the basis of information collected and reviewed to this point.

2.5.2 Stage 2: Technical Data Generation

The second stage, disassembly or decompilation of the original product, is the most time-consuming aspect of the project. In this stage, reverse engineers attempt to construct a characterization of the system by accumulating all of the technical data and instructions of how the product works. The objective is to develop a complete and unrestricted technical data package which will be sufficient for both fabrication and procurement of the part in the future. The engineering drawing defines the configuration of the component, and the technical package contains all additional inspection and quality assurance requirements to manufacture the part.

2.5.3 Stage 3: Design Verification

In the third stage of reverse engineering, reverse engineers try to verify that the data generated by disassembly or decompilation is an accurate reconstruction the original system. The design generated in stage 2 is verified by testing of a preliminary technical data package (PTDP) on one or many levels. The verification method requires two separate operations to be conducted, yet the outcome is dependent on the completeness of the data to achieve success in both areas. The two operations are prototype fabrication and prototype testing. Engineers verify the accuracy and validity of their designs by testing the system, creating prototypes, and experimenting with the results.

2.5.4 Stage 4: Project Implementation

The final stage of the reverse engineering process is the introduction of a new product into the marketplace. With the inclusion of all test, inspection and quality assurance reports, the data have completely become the complete technical data package

(CTDP). The delivery of prototypes, the engineering and the economic summary, and the CTDP with procurement requirements form the final TDP. These new products are often innovations of the original product with competitive designs, features, or capabilities. These products may also be adaptations of the original product for use with other integrated systems, such as different platforms of computer operating systems.

Often different groups of engineers perform each step separately, using only documents to exchange the information learned at each step. This is to prevent duplication of the original technology, which may violate copyright. By contrast, reverse engineering creates a different implementation with the same functionality.

CHAPTER III

RAPID PROTOTYPING AND MANUFACTURING

3.1 Introduction

The key to regaining competitiveness in most design and manufacturing industries are quality, productivity, reduced costs, customer satisfaction, and responsiveness in bringing new products to the marketplace. One of the methods of attaining these attributes is Rapid Prototyping. Rapid Prototyping (RP) takes information from a three-dimensional (3D) computer-aided design (CAD) database and produces a solid model (prototype) of the design. One can turn a design concept into a solid prototype and test it for form, fit, and function at a fraction of a cost and time of traditional prototyping methods. The traditional method of prototyping a part is machining, which can require significant lead times from several days to many weeks, depending on the complexity of the part and availability of materials, equipment and labor. A number of RP technologies such as stereolithiography, selective laser sintering, fused deposition modeling, and 3D printing are available for producing plastic parts directly from design data created in any one of many commercially available CAD systems.

3.2 What is Rapid Prototyping?

Rapid Prototyping refers to the fabrication of a three dimensional physical models directly from a computer-aided design (CAD). This additive manufacturing process provides designers and engineers the capability to literally print out their ideas in three dimensions. According to *Wohler's Report 2000*, RP is defined as: a special case of machine technology that quickly produces models and prototype parts from 3-D data using an additive approach to form the physical models [5]. The generic RP process is shown in Figure 2 [2]. The RP process provides a fast and inexpensive alternative for producing prototypes and functional models as compared to the conventional routes for part production.

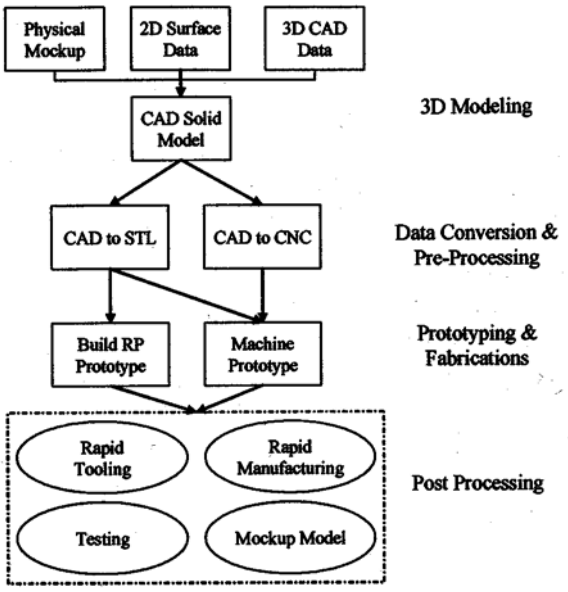


Figure 2 Generic Rapid Prototyping process

The advantage of building a part in layers is that it allows you to build a complex shapes that would be virtually impossible to machine, in addition to more simple designs.

RP can build intricate internal structures, parts inside of parts, and very thin-wall features just as simple as building a cube.

All of the RP process constructs objects by producing very thin cross section of the part, one on top of the other, until the solid physical part is completed. This simplifies the intricate three-dimensional construction process in that essentially two-dimensional slices are being created and stacked together. For example, instead of trying to cut out a sphere with a detailed machining process, stacks of various sized “circles” are built consecutively in the RP machine to create the sphere with ease.

RP also decreases the amount of operation time required to build parts. The RP machines, once started, usually run unattended until the part is complete. This comes after the operator spends a small amount of time setting up the control program. Afterwards, some form of cleanup operation is usually necessary, generally referred to as post processing. Models can usually be built with in hours, and the build materials for most processes are inexpensive. Some RP machines are small and environmentally friendly so they can be placed into a designer’s office.

3.3 Applications of RP

Most of the RP parts are finished or touched up before they are used in specific areas of applications. Applications can be grouped into design, engineering analysis and planning and tooling and manufacturing. A wide range of industries can benefit from RP and these include, but are not limited to, aerospace, biomedical, consumer, electrical, and electronics products. There are many types and classes of physical prototypes as shown in

Figure 3 but their main purpose is to minimize risk during the product development process. Some of the specific applications of RP follow [13]:

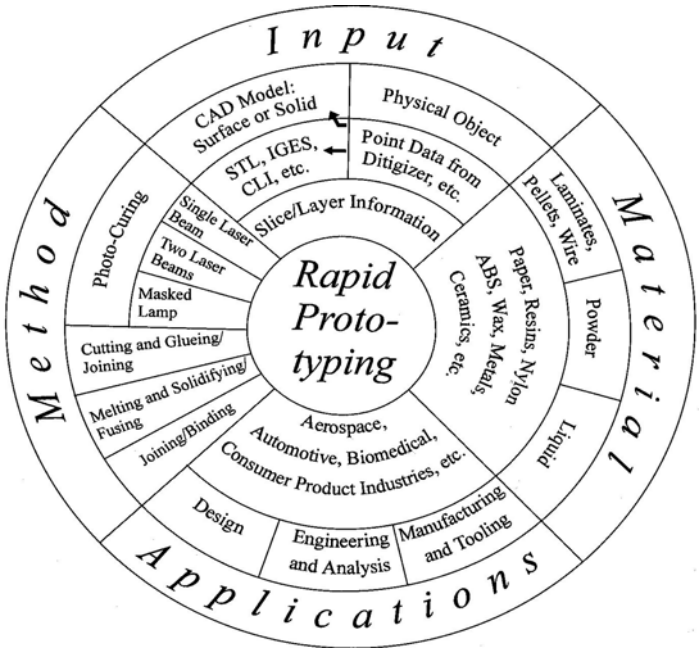


Figure 3 Rapid Prototyping Wheel

- Communication of product characteristics
- Engineering concept definition
- Form, fit and function testing
- Engineering change clarification
- Client presentations and consumer evaluations
- Bid proposals and regulation certification
- Styling, ergonomic studies
- Facilitate meeting schedule and making milestones

- Masters if silicone rubber tooling
- Masters of spray metal tooling (all process)
- Masters of epoxy tooling to be used for injection molding
- Master/pattern for investment casting
- Tooling for injection molding

3.4 RP fundamentals

All the prototypes made with current and evolving RP processes have several features in common. A solid or surface CAD model is electronically sectioned into layers of predetermined thickness. These sections define the shape of the part collectively. Information about each section is then electronically transmitted to the RP machine layer by layer. The RP machine processes materials only at “solid” areas of the section. Subsequent layers are sequentially processed until the part is complete. It is this sequential, layered, or lithographic approach to the parts manufacturing that defines RP. The RP process basically uses the following steps to make prototypes:

- Create a CAD model of the design.
- Convert the CAD model to STL (Stereolithography) file format.
- Slice the STL file into 2-D cross-sectional layers.
- Grow the prototype.
- Postprocessing

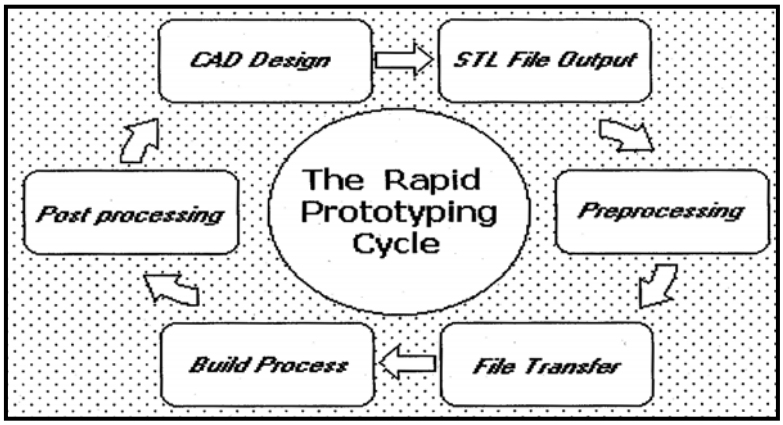


Figure 4 The Rapid Prototyping Cycle [4]

3.4.1 Creation of Solid Models

The first step in creating a prototype is the creation of CAD solid model. RP requires that we make a fully closed, water-tight model. A solid is a volume completely bounded by surfaces, which means that edges of all surfaces must be coincident with one, and only one, other surface edge. Unlike wire-frame and other surface modeling, solid modeling stores volume information. A CAD solid model not only captures the complete geometry of an object, it can also differentiate the inside and the outside of the space of that object. Many other volume related data can be obtained from the model. Solid models can be created using a CAD software package such as AutoCAD, Pro/Engineer, CATIA, SolidWorks, or many other commercially available solid modeling programs.

3.4.2 Conversion to STL File

Once a solid model is created and saved, it is then converted to a special file format known as STL (Stereolithography). This file format originated from 3D systems which pioneered the stereolithography process. An STL file format represents the virtual CAD model of object to be prototyped as a collection of triangular facets. These triangular facets, when taken together, describe a polyhedral approximation of the object's surface that is polyhedral approximation of the boundary between material and non material.

3.4.3 Slicing the File

The file is taken from its 3D model surfaces and converted to many triangles, a step referred to as slicing. The more complex the object, the more triangles are required, and thus the bigger the file that makes up the CAD model as well a support structure for the part to be grown on. The sliced object is saved as STL file and is now in format the RP computer recognizes.

3.4.4 Making or "Growing" the Prototype

The part is submitted to the RP computer and the machine runs until the part is complete. RP machines build one layer at a time from polymers, paper, or powdered metals. Most machines are autonomous needing little human intervention and the build times vary depending on size and number of parts required.

3.4.5 Postprocessing

The final step in RP is Postprocessing. It essentially consists of part removal and cleaning and of postcuring and finishing. This step generally involves manual operations

where an operator does the postprocessing with extreme care. Otherwise the part may be damaged and may need to be prototyped again. The tasks for post processing are different for different prototyping systems. Part removal and cleaning refers to taking the prototype out of the prototyping machine and removing excess materials, including support materials, which may have remained on the part.

3.5 Problems with STL File Format

While the STL file format is meeting the needs of the industries that are using RP and while it is *de facto* standard in RP industry, it has some inadequacies. Some of these inadequacies are due to the very nature of the STL file format as it does not contain topological data. Also many CAD vendors use tessellation algorithms that are not robust. Consequently, they tend to create polygonal approximation models, which exhibit the following types of problems:

3.5.1 Gaps (Cracks, Holes, and Punctures) Indicating Missing Faces

When a solid model is converted into an STL file format, the solid model forms are replaced with a simplified mathematical form (triangles). However, if the simplified operation is not done properly, it introduces undesirable geometric anomalies, such as holes or gaps in the boundary surface.

3.5.2 Inconsistent Normals

In general, surface normals should be pointed outward. However, the normals of some surfaces could be flipped over, thus becoming inconsistent with the outward orientation of the original surface.

3.5.3 Incorrect Normals

Sometimes, surface normals stored in the STL file are not the same as those computed from the vertices of the corresponding surfaces.

3.5.4 Incorrect Interconnections

Facets may sometimes intersect at locations other than their edges resulting in overlapping facets.

3.5.5 Internal Wall Structure

Geometric algorithms are used for closing gaps in STL files. However, faulty geometric algorithms could generate internal walls and structures that can cause discontinuities in the solidification of the material.

3.5.6 Facet Degeneracy

Degeneration of facets occurs when they may not represent a finite area and consequently have no normals. A geometric degeneration takes place when all the vertices of the facet are distinct and all the edges of the facet are collinear. A topological degeneracy takes place when two or more vertices of a face coincide.

3.5.7 Inconsistencies

Sometimes two STL files are combined to create a prototype. If these STL files are created using different tolerance values, it will lead to inconsistencies such as gaps [5].

3.6 Development of RP Systems

Currently, there are various new technologies that are available in the market; these technologies allow “automatic” production of prototype parts directly from a solid model.

3.6.1 3D Systems’ Stereolithography Process

This technique creates three-dimensional model from liquid photosensitive polymer resins that solidify when exposed to ultraviolet light. The model is built on a platform situated just below the surface of a vat of photopolymer material. The photopolymer is a low-viscosity liquid until it is exposed to UV light. The UV light causes the photopolymer molecules to polymerize, linking together to form a network. The process turns a liquid into a solid. The beam from UV laser is directed into the vat by a mirror system that is controlled by a computer.

A software program slices the 3D CAD model into layers. The laser beam traces each layer onto the surface of the vat, which solidifies as a result of the exposure to UV light. The solidified layer is then lowered into the vat so that another layer of liquid can be exposed to the laser. The process is repeated until all cross-sections are built into solid model of the original CAD model.

3.6.2 3D System’s Selective Laser Sintering

The selective laser sintering (SLS) process, introduced by DTM, uses a laser to sinter a powdered material into the prototype shape. In many ways SLS is similar to stereolithography apparatus (SLA) except that the laser is used to sinter and fuse powder

rather than photocure the polymeric liquid. In this process a thin layer of thermoplastic powder or metal qis spread by a roller over the surface of a build cylinder and heated to just below its melting point by infrared heating panels at the side of the cylinder. Then a laser sinters and fuses the desired pattern of the first slice of the object in the powder. Next, this fused slice descends one object layer, the roller spreads out another layer of powder, and process continues until the part is built.

3.6.3 Helisys' Laminated Object Manufacturing

Helisys introduced the laminated object manufacturing (LOM) technique, which creates parts from laminated sheets of paper, plastic, or metal by a laser. This technique only requires a cut of the outline of each layer into a sheet of paper instead of crosshatching the entire part cross section. After each outline has been cut, the roll paper is advanced then a new layer is glued into the stack, and the process is repeated until the part is made.

3.6.4 Stratasys' Fused Deposition Modeling

Fused Deposition Modeling was introduced by Stratasys in 1991. FDM extrudes a thin stream of melted acrylnonitrile-butaidene-styrene (ABS) thermoplastic polymer or wax through an extruder head whose position is controlled by a computer. Parts are built by moving the extruder head through the volume of the part. The process fabricates 3D parts from a buildup of 2D layers.

3.6.5 Solidscape’s 3D printing

Solidscape introduced 3 D printing technology that uses dual ink printer heads to deposit both thermoplastic part material and a wax support structure. The device uses a milling operation after each layer is deposited to create very thin, precise layers.

CHAPTER IV

FUSED DEPOSITION MODELING

Fused Deposition Modeling (FDM) is an extrusion based rapid prototyping process. FDM system relies on the standard STL data file for input, and is capable of using multiple build materials in a build/support relationship. This chapter describes Rapid Prototyping systems whose initial form of material is solid. The solid based RP systems studied in the present thesis include Stratasys' FDM system.

4.1 Company Profile

In 1988, Scott Crump, the president and CEO of Stratasys Inc. developed fused deposition modeling (FDM) process. The FDM line of rapid prototyping systems allows designers to produce accurate, functional prototypes for testing and final design verification. These products can also be used produce tooling patterns and masters for casting, room temperature vulcanized (RTV) molds and spray-metal tooling applications. Current FDM systems offered include the FDM Vantage, FDM Titan, FDM 8000, and FDM Maxum.

Using the patented FDM and polyjet rapid prototyping process, Stratasys RP systems can create precision three–dimensional prototyping parts directly from 3D systems for use in testing forms, fit and function throughout the design and development process.

4.2 Fused Deposition Modeling System Hardware and Software

The FDM system consists of a Stratasys 3D Modeler (a floor unit), MicroScribe G2 3D digitizer, and a personal computer. The 3D modeler has a build volume of 203mm x 203mm with 305mm.

4.2.1 Software

All the machines use the *Catalyst* software, manufactured by Stratasys, Inc., to manipulate and prepare the incoming STL data for use in FDM machines. The 3D modeling software used is *SolidWorks 2005* and the reverse engineering software is *RevWorks.* We can create parametric models quickly and easily with RevWorks and collect part data and capture design intent more quickly and precisely than with other technologies which rely on point-cloud scanning. With RevWorks, we need less data and time to create accurate, parametric, editable part definitions directly inside SolidWorks software. RevWorks adds many time-saving tools for capturing component data directly into parts and assemblies, including 2D and 3D sketch tools, SnapScan, and DirectSurf.

4.2.2 Build Materials

The FDMs can be equipped to build with investment casting wax, acrylonitrile butadiene styrene (ABS) plastic, medical grade ABS thermoplastic, and Elastomer,

although ABS is currently used the most. The build and support materials come in filament form of about 0.070 inches in diameter and rolled up on spools in the form of a cartridge. The cartridge is loaded in front of the machine.

4.2.3 The Extrusion Head

The extrusion head is the key to FDM technology. The head is compact, removable unit and consists of the following components as shown in Figure 5 [15].

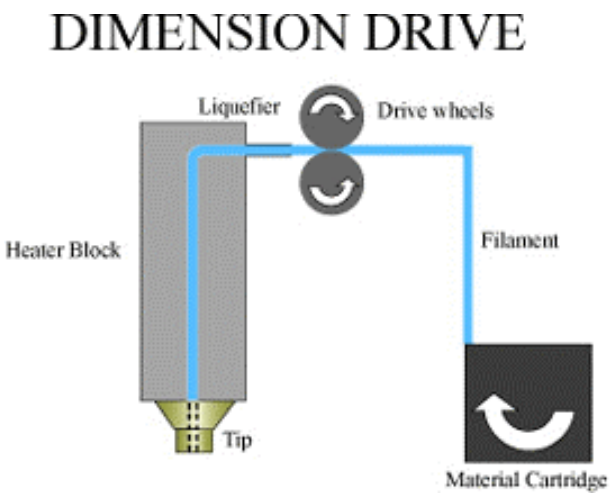


Figure 5 The Extrusion Head

4.2.4 Build Substrate

The foam substrate is an expendible work table onto which parts are built. The substance is about one-inch thick and is fastened by means of pins/clips.

4.3 Fused Deposition Modeling Operation

4.3.1 Computer Aided Design File Preparation

Before, building a part, the STL file has to be converted into the machine language understood by the FDM. The *catalyst* software is used for this purpose. The STL file is read into *catalyst*, and is displayed graphically on screen in the Cartesian coordinate system (–x, -y, -z). A three-dimensional box representing the maximum build envelope of the FDM. *Catalyst* gives the options on the FDM system being used, the material thickness, and the build support materials.

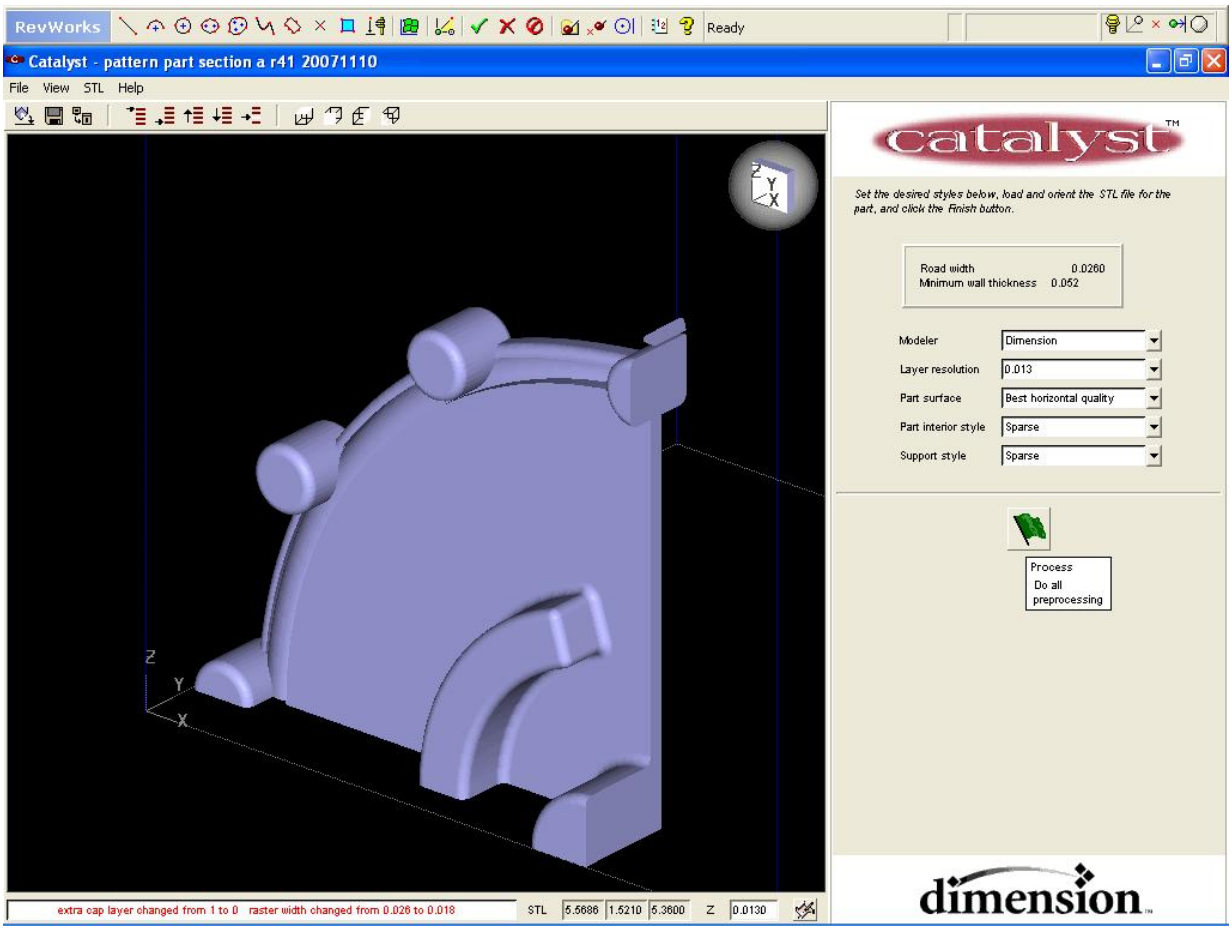


Figure 6 An STL file as viewed by Catalyst

4.3.2 Part Size

First, it must be affirmed that the part will fit into the design envelope; if not it will either have to be scaled down to fit, or be sectioned so that the pieces can be built separately and then bonded together later. For instance, if the part fits in –x and –y but its too tall in the –z, catalyst can be used to section the part by slicing to a certain height, then starting a new build later at that height and finishing the part. This technique results in flat mating surfaces with no alignment bosses or slots.

4.3.3 Orientation

Once the part has been deemed an appropriate build size, the part should be oriented in an optimum position for building. The shape of the part plays a major role in this, in that some orientations may require less supporting of overhangs than others.

4.3.4 Slicing

Once the part has been properly oriented and /or scaled it must be sliced. Slicing is a software operation that creates thin, horizontal cross sections of the STL file that will later be used to create the control code for the machine. In *catalyst* the slice thickness can be changed before slicing, the typical slices range from .005 inches to .015 inches. Thinner slices can be used for higher definition models.

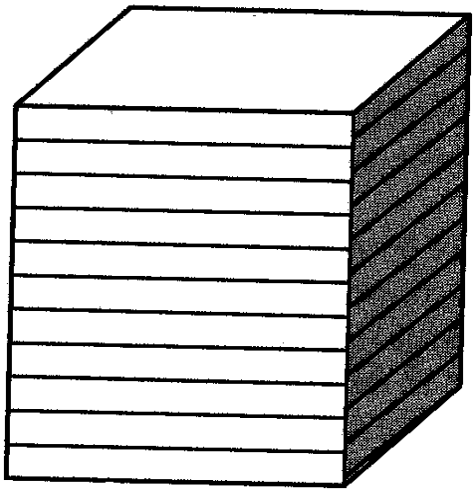


Figure 7 Sliced Modal

4.3.5 Building a Part

Once the STL file has been sent to the FDM from the PC, the process begins by moving the head to the extreme –x, -y position and raises the platen to a point where the foam substrate is just below the heated tips. The user then presses the button to begin building. After that the FDM will build the part completely.

4.3.6 Finishing an FDM Part

FDM parts are usually some of the easiest rapid prototyped parts to finish. FDM features the Breakaway Support System (BST), which allows the support material to be peeled away easily by hand with knife or pliers. The materials are easy to finish by sanding, and the ABS plastic parts may be very smooth by wiping them down with a cloth moistened in acetone or similar light solvent. The parts require very little finishing before they are ready, depending on their application.

4.4 Products

Stratasys' has developed many different products to facilitate different needs of Rapid Prototyping. The technical specifications of several solid based RP systems are as follows:

- FDM Vantage SE
- FDM Titan
- FDM Maxum
- Prodigy Plus
- Dimension
- Eden 260
- Eden 333

4.5 Advantages of FDM System

- No postcuring.
- Variety of materials
- Easy material changeover
- Low end, economical, office environment machines
- Fast build speeds on small/hollow geometries
- Low entry price

4.6 Disadvantages of FDM System

- Surface finish is not as good as production parts
- Weak Z axis
- Slow build speed on larger/dense parts

CHAPTER V

LABORATORY FACILITY

5.1 Experimental Setup

The laboratory setup consists of Stratasys' Dimension BST, MicroScribe G2 3D digitizer, personal computer and a water pump housing from 1913 Rambler car. The computer, Digitizer and the prototyping machine, Dimension BST are connected using standard TCP/IP networking. The reverse engineering software used to capture the geometry is RevWorks and it is fully integrated into SolidWorks interface. In linking SolidWorks to 3D digitizer or coordinate measuring machine (CMM), RevWorks opens the door to greatly enhanced productivity allowing capturing the design intent of the parts more quickly. The computer system is equipped with Catalyst software which converts/slices the 3D CAD model into STL (Stereolithography) format and also adds support structure for the part to be grown on. The sliced object is now in format the RP computer recognizes. The RP machine, Dimension BST is connected to the computer through Local Area Network (LAN).

5.2 Reverse Engineering Tools

Like many coordinate measuring machines (CMM) MicroScribe G2 digitizer captures the physical properties of three-dimensional objects and translates them into complete 3D models with an accuracy of up to 0.015-inch. It uses the software called RevWorks which is used to translate the point or scan data generated from MicroScribe digitizer into a 3D CAD model. RevWorks adds direct reverse engineering capability by connecting the 3D digitizer to SolidWorks.

By selecting options presented within the familiar Solid Works interface, point data and features from the actual component are directly captured into part and assembly documents. The strength of this approach is to collect only the data needed to model the part. Further, once a feature is collected, the measured dimensions can be immediately adjusted to preferred values. RevWorks interacts directly with SolidWorks to place the geometry it creates from digitized data directly onto sketch planes and 3D sketches. The RevWorks toolbar is shown in Figure 8 as it is seen when digitizing using MicroScribe G2.

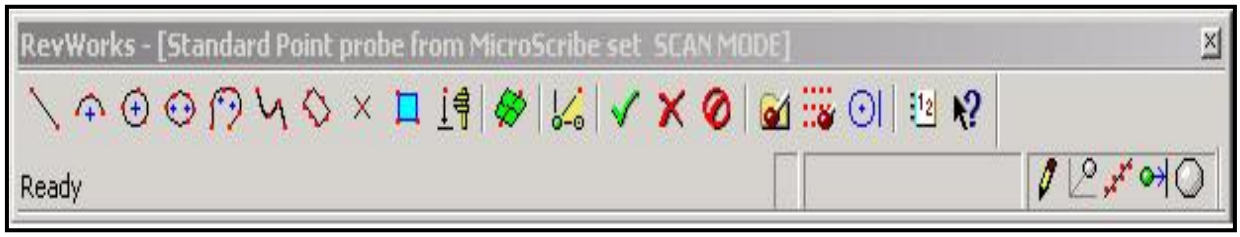


Figure 8 RevWorks Toolbar

The RevWorks toolbar contains a series of buttons that provide easy access to RevWorks functions. Each button on the RevWorks toolbar contains an icon and performs a function. For certain functions, there are a variety of methods.

RevWorks offers two options for collecting the point data used to make measurements and create features; Single Point Mode and Scan Point Mode. While operating in Single Point Mode, one press of a key or button causes one point to be taken. Data collected for 2D features in Single Point Mode may be taken at any distance from the current sketch plane and the data is automatically projected to the currently active sketch plane. For 3D features the data is collected directly into a SolidWorks 3D sketch.

The Scan Point Mode allows capturing data using Snap Scanning or freeform scanning. Snap Scanning limits data collection to a user-definable collection band buffering the active sketch plane. This technique allows you to accurately collect data on a sectional plane without having actual markings or edges on the part to work from. With freeform scanning, there is an option to apply Interval Filter, which limits the data collected by definable measures such as time or distance. Freeform scanning allows collecting streaming data on a freeform surface or along a 3D path and control the amount of information captured. These methods give great flexibility for collecting part features and characteristics.

5.3 Procedure

5.3.1 Work Piece Setup

It is very important to properly clamp the part to be digitized to the fixture. The part is set on the vice and clamped to the table or the workstation and is oriented horizontally or vertically to achieve the true geometry. The part is set close to the MicroScribe G2 digitizer so that the digitizing arm can cover the whole part with much

ease. The Figure 9 shows the workstation setup at the Component Evalution and Prototyping Lab at Cleveland State University.



Figure 9 Setup at the Component Evalution and Prototyping Lab at CSU

5.3.2 Datum Setup

The digitizing device has its own internal coordinate system also known as the "device coordinate system". SolidWorks also has its own coordinate system called model space or "sketch coordinate system". By using datums, a coordinate system is defined relative to the part being digitized. Once the datum plane for the part is defined, then the part is aligned with the SolidWorks model space and screen display. Datums convert device coordinates into part coordinates that align with the SolidWorks coordinate system. To create a datum, using RevWorks menu, a SolidWorks part window must be opened. A screenshot to create the datum is shown in Figure 10 and Figure11.

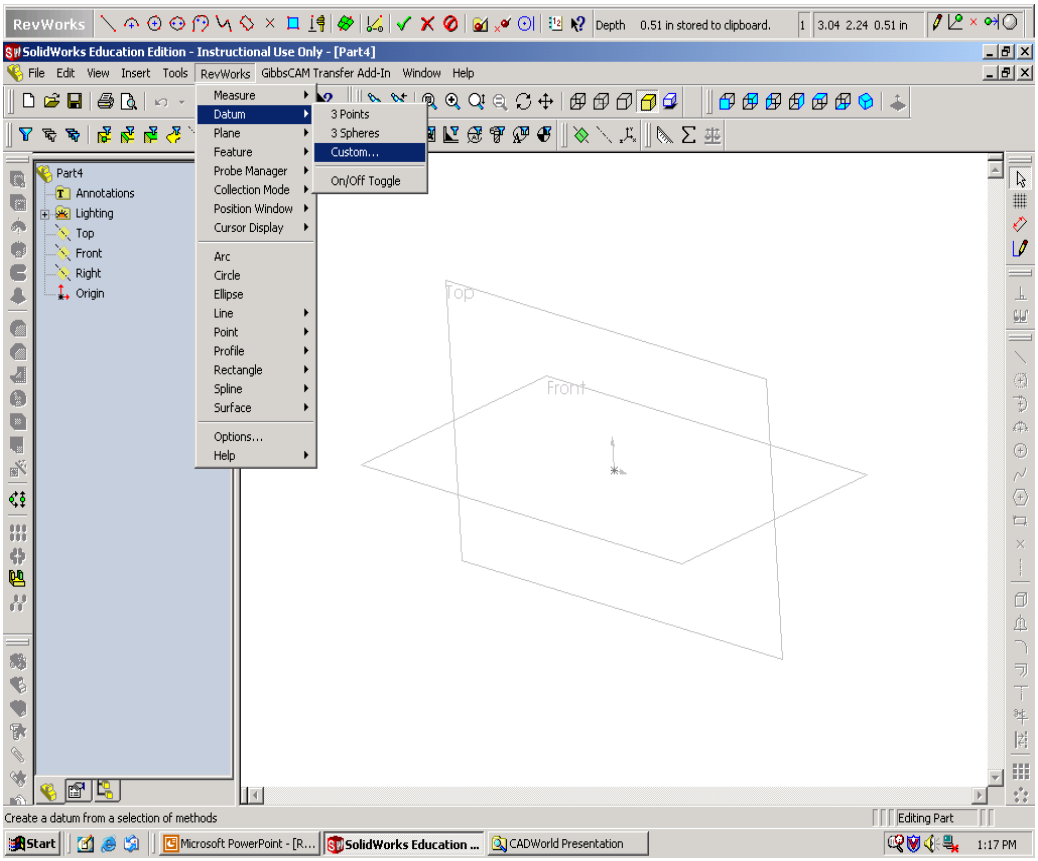


Figure 10 Datum setup from the pull down menu of RevWORKS

By setting the datum for a part, the part is aligned with the SolidWorks model space and screen display. Datums convert the device coordinates into part coordinates that align with the SolidWorks coordinate system. After digitizing the datum, RevWorks automatically generates the custom datum, and the settings immediately take effect. With the datum in effect, data collected from the part aligns properly with the SolidWorks coordinate system. The point cloud data collected from the surface of the object are transformed as 3D CAD model.

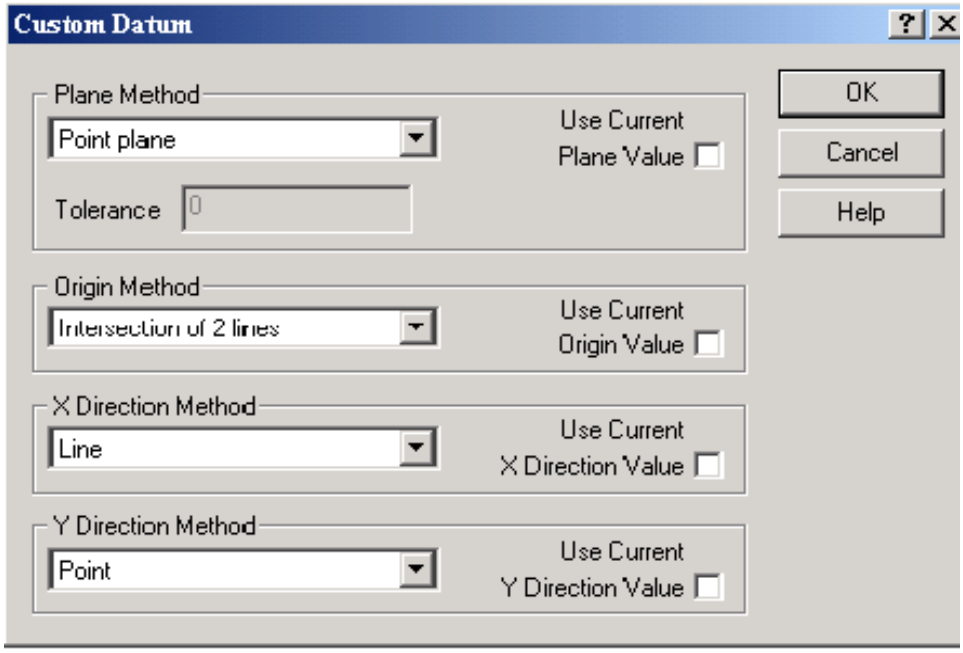


Figure 11 Menu for Datum selection

5.3.3 MicroScribe G2 Digitizer

The MicroScribe G2 (Figure 12) digitizer gives the physical representation of a three-dimensional Cartesian coordinate system. The digitizer measures the surface of the object using a contact probe, a highly sensitive pressure-sensing device that is activated by any contact with an object. The linear distances from the three axes to the position of the probe are ascertained, thus giving the x, y and z coordinates of the surface. The counterbalanced mechanical arm is equipped with precision bearings for smooth, effortless manipulation. Each joint uses digital optical sensors, which are immune from any environmental noise and interference. It all makes for a versatile system that can work in most any environment and be used with solid objects of most any material. The MicroScribe G2 digitizer has an accuracy of up to 0.009-inch.



Figure 12 Microscribe G2 Digitizer

5.3.4 Dimension BST

Dimension Printing is essentially the mainstream division of Stratasys based on the same core Fused Deposition Modelling (FDM) technology. Fused Deposition Modelling is unlike many of the other layer-based manufacturing methods. While the majorities rely on lasers or light to cure layers of resin or printing technology to solidify material, FDM uses a heated tip to incrementally deposit layers of molten ABS, which are fed into the system from cartridges of filament. In essence, each layer is built on top of the previous layer using a build platform which moves vertically downwards.

The Dimension BST has a footprint of 686mm x 914 mm as shown in Figure 13. Unlike some other systems, the machine generates very little heat. Build volume is a perfectly respectable 203mm x 203mm with 305mm in Z direction, and material is

supplied in individual cartridges for build and support material which are loaded at the front of the machine – they've even labeled **M** and **S** so that they don't get mixed up. The material filament in each machine is loaded automatically and fed up to the heated deposition tip at the top of the unit.



Figure 13 Stratasys Dimension BST 3D Printer

5.3.5 Build process

Rather than being tooled from a solid body, 3D models made by rapid prototyping technology are built by the addition of material and the phase transition of the materials from a fluid to a liquid state. In this method a model created in a CAD program is imported into a software program specifically designed to work with FDM machine. The data for the model is saved as an STL (stereolithography) file for interpretation.

The starting point is to connect the machine to the network. Once done, we are ready to use the *Catalyst* software supplied with the system. *Catalyst* provides us with STL import, build volume definition and slicing tools. It allows us to import the STL part files and orientate them within the build volume. It also allows us to arrange multiples within a single build – bearing in mind that the system can only nest in a planar manner. The machine automatically generates the supports required.

Once the build volume is ready, send the file to the 'print queue', which provides a number of job queuing and administration tools. Building is carried out on basic platforms which are made of ABS Plastic and these are easily installed or removed from the system using simple clips. The machine builds the prototype by extruding a thin stream of semiliquid ABS plastic. Build layer thickness can be toggled between 0.01 in (0.245 mm) to 0.013 in (0.33 mm), and depending on which you use the build speed varies according to layer thickness, the volume depositing, the build style and the support configuration. To build each layer, the extrusion head deposits the outline of the layer first and then fills each layer according raster dimensions set by the operator. The raster fill of the outline is a series of straight line segments that link together and are uniformly spaced. As each layer is deposited it fuses to the previous one, creating a solid model.

In terms of horizontal resolution, the Dimension isn't intended to be a high-resolution machine. When deposited, the molten ABS filament creates a bead around 0.5mm.The Stratasys Dimension BST has a heated head that extrudes the breakaway support system. As with the ABS plastic, this material is deposited in layers on the X-Y plane and serves to support any overhanging portions of the prototype's geometry. As the name implies, the support material is easily broken away from the model.

The ABS P400 plastic used is a durable ABS-based material that is appropriate for concept models as well as for testing of form, fit, and some function. The ABS P400 plastic is impact resistant, has a relatively high tensile strength, and is heat, scratch, and chemical resistant. The material has a high thermal expansion for a plastic and is lower in cost than most engineering thermoplastics. However, ABS plastic has limited weather resistant and is not very resistant to solvents.

5.4 FDM and Sand Casting

The sand casting process is relatively simple, and the production of the sand molds and cast metal parts is relatively quick. However, the fabrication of the patterns to produce the sand molds can be time consuming. The application of FDM to the sand casting process reduces the pattern development time to expedite the receipt of prototype or production sand cast parts.

The rapid prototyped part must be able to withstand the chemicals in the sand, be abrasion resistant and be able to withstand the ramming forces that are applied to pack the sand. Unlike many other rapid prototyping technologies, FDM meets these requirements with its ABS material.

CHAPTER VI

APPLICATION OF REVERSE ENGINEERING AND RAPID PROTOTYPING TO MANUFACTURING

Reverse engineering is a process used when an existing component must be reproduced, but the designs are not accessible. The part must be measured and redrawn to obtain new records, as well as to allow for remanufacture of the component. This can be done several ways, from simply measuring the dimensions with calipers and recording the data to be redrawn, to today's sophisticated techniques of translating x-ray imaging or 3 D LASER scan data into CAD data files. The application of reverse engineering spans a variety of industries, and can be accomplished with as many techniques. Rapid Prototyping is applicable to any industry engaged in the production of consumer or engineering products, or tooling. Thus RP and associated process are used extensively for automotive, aerospace, aeronautics, railway and electronic applications. RP is of strategic importance whenever product innovation or time–to-market is important. The present chapter discusses its application to a vintage automobile component. The component is a water pump housing from 1918 Rambler car.

6.1 Rapid Prototyping and Manufacturing

The geometry was captured in the Component Evaluation and Prototyping Laboratory at CSU. The original component is secured firmly to the vice and the geometry is captured with the help of Microscribe G2 digitizer, a coordinate measuring machine as shown in Figure 9. The CAD file is created by CMM measurement of an existing part. Reverse Engineering by RP follows a few basic steps.

The geometry of the component, the water pump housing in this case, is captured in much the same way as initially building a SolidWorks modal. The RevWorks program, which is closely linked to SolidWorks, is utilized. For example, if a cylindrical feature is required, a sketch is opened and a circle is selected from the RevWorks toolbar that was illustrated in Figure 8. Several points are digitized around the cylinder, and the RevWorks software generates the best-fit circle. At this point the user may change the diameter or location of the circle based on measurements that he made. For example, if the diameter of the digitized circle is 0.99878, the user might change it to 1.00 inches. Once the sketch of the circle is complete, the user digitizes the height of the cylinder and then extrudes the circle to that height to complete the cylinder. This procedure is also applicable to other features shown on the toolbar in Figure 8. Upon completion of the capturing of the geometry, the user has a complete SolidWorks file, including the Feature Manager Tree of the part. The next step in the creation of the master pattern is to create a CAD file. Once data is captured, it must be converted into actual surface representations. Here, it's done with the help of software called RevWorks, designed for this specific purpose and is exported in STL file format for RP. Each feature is incorporated in the feature manager tree. The advantage of feature manager tree is that, it is same as

initiating the drawing from a part. An STL format is machine-readable format for the Stratasys Dimension BST machine. Once the CAD file is generated then the necessary material properties are applied to the part. The CAD files are used to produce prototype models using FDM prototyping method.

6.2 Application of Rapid Prototyping to Fabricate a Pattern

Once the geometry is captured and the CAD modal is ready, the necessary shrinkage allowances are applied to the CAD modal. The FDMABS master pattern is made oversize to allow for the metal contraction as it cools down to room temperature. This is achieved by making the pattern oversize. To account for shrinking, the pattern must be made oversize by these factors, on the average. These are linear factors and apply in each direction. These shrinkage allowance are only approximate, because the exact allowance is determined the shape and size of the casting. In addition, different parts of the casting might require a different shrinkage allowance. A shrinkage factor of 10 % is considered for the pattern to be cast in Aluminum [22]. Once the shrinkage factor has been applied, the SolidWorks file is saved as an STL file.

The ABS plastic pattern (master pattern) made in the Dimension BST machine is used to cast the prototype in Aluminum. The pattern made is divided into four cross-sections; because the maximum size of the part that can be made in Dimension BST is limited to 12 x 8 x 8 in. Once the four parts are made then the individual parts are glued together to make the master pattern. The Figure 14 shows a visual comparison of the sample part and the FDMABS pattern. The FDM-ABS master pattern is made slightly bigger than the actual part to allow for the various shrinkages.



Figure 14 Comparison of sample part and ABS pattern

6.3 Sand Casting Design

Sand casting is an economical way to produce metal prototypes. The most common type of metal prototyping is aluminum casting. Sand casting is a faster and less expensive process than die casting or investment casting. The process derives its name from the use of sand to create the molds into which molten metal is cast. The molds are created by packing sand around a pattern. The sand holds its shape with the addition of clay and water (green sand) or a chemical binder (dry sand). After the sand has been packed, the pattern is removed, and metal is poured into the cavity in the sand mold. Once cooled, the sand is broken away from the cast metal part. It is a cost effective and efficient process for small lot production, and yet, when using automated equipment, it is an effective manufacturing process for high volume production.

In the casting industry, reverse engineering (RE) is the process of using an existing part as a model to create a CAD file to produce either a prototype or production parts. The following features are to be carefully selected for better casting process. While designing a pattern the designer should take into account the following: the parting line, finish, the draft, the presence of ribs, bosses, webs, and recesses, and the machining allowance. In general uniform walls are preferred with a maximum wall thickness not to exceed 5 inches and a minimum wall thickness of .25 inches over a 5 inch span max.

The mark or line on a casting formed at the junction of cope and drag section where the mold parts is called parting line. Its location and draft are determined during the design process. It is normally removed by grinding and or sanding. The tolerances across parting lines are added to basic linear tolerances. Determining the position of the parting line is a critical step in the casting design. Parting line mismatch, and parting line and seam flash extension allowances should nor exceed .020". Maximum parting line seam flash extension material is about .015".

Basic linear tolerances refer to dimensional tolerances that are attainable within the same mold half. Additional tolerances for machine allowances, coring and parting lines should also be considered in dimensioning the overall casting.

Pattern Draft is the taper allowed on the vertical surface of a pattern to permit withdrawal of the casting from the mold. Casting draft is the actual draft angle on the casting. It is determined during the design process. To facilitate the removal of the pattern from the weak, brittle molding sand cast draft should be defined and accounted for. Standard draft for sand casting is 2 degrees with a minimum of about 1 degree for external and internal features.

The design should not contain abrupt section changes. Fillets and tapers are preferred to sharp steps. If a section change of over 2:1 thickness ratio is unavoidable, there are two alternatives: design two separate castings to be assembled together, or use a wedge form between the unequal sections. The taper of the wedged area should not exceed 1:4.Improper rib, web and corner design can lead to sink spots. In general web or wall thickness should as a minimum be 0.10" Aluminum.

Additional cast on material (machine stock) that is to be machined away from the surface of the casting. Finish allowances should be specified on the part drawing using commonly recognized symbols for finish allowance. Finish allowance of 4mm is considered in the present pattern. As cast surface finish is typically 200 500 RMS. Post machining operation should be accounted for in material allowances should better surface be required. The typical tolerances are shown in Table 1 [22].

Greatest Dimension	Tolerance on One Side of Parting Line	Tolerance if Dimension Crosses Parting Line	Tolerance of Flatness
0(0) – 6" (152.4)	± .063" (1.6)	± .090" (2.3)	± .060" (1.5)
6" (152.4) – 12"(304.8)	± .094" (2.4)	± .125" (3.2)	± .090" (2.3)
12" (304.8) – 18" (457.2)	± .125" (3.2)	± .188" (4.8)	± .125" (3.2)
18" (457.2) – 24"(609.6)	± .188" (4.8)	± .250" (6.4)	± .188" (4.8)

Draft Angles

Height of Draw	Draft angle
.125" (3.2) – .250" (6.4)	8° – 15°
.250 (6.4) - .500" (12.7)	3° – 7°
.500" (12.7) – 1.000" (25.4)	2° – 3°
1.000" (25.4) – and up	1° – 2°

Table 1 Dimension Tolerance Table

6.4 Process Overview

In sand casting, there are two components to the tool. The cope is the top side of the tool. Depending on the type of metal that is poured, it may incorporate the sprue, gates, vents, risers and filters. The drag is the bottom part of the tool as shown in the Figure 15. Like the cope, its design is dependent on the cast metal. Usually, the drag incorporates the runners, gates and wells. When undercuts are present, or if the cast part has hollow areas, loose cores, which are also made of sand, are inserted into the cope and drag.



Figure 15 Cope and Drag

The process begins with the design of the cast part and the metal delivery pathways in the mold. This data is then used to construct a pattern that forms the cope and drag. The pattern is mounted in a four-sided box called a flask. Sand is then poured

into the flask, and it is packed tightly against the pattern. Binders, which are either clay (green sand) or chemical agents (dry sand), hold the compacted sand together.

Molten metal is poured into the mold through the sprue. It flows through the runners and gates into the part cavity. The metal also fills the riser, which acts as a reservoir that continues to feed the part cavity as the metal cools and shrinks. The metal is then allowed to cool and solidify, and the sand is broken away from the parts.



Figure 16 Reverse Engineered Part just out of mould

Although relatively simple in concept, sand casting requires a great deal of experience. The challenge is to design a tool that provides suitable pathways for a sufficient, non-turbulent flow of metal into the part cavity and has proper venting for the release of any gases. Failure to do so will yield a casting with voids and imperfections.

Using FDM for pattern creation, sand casters have an efficient and effective way of prototyping the tool design, proceeding directly to production casting.



Figure 17 Comparison of the Sample Part and Reverse Engineered Part

The shrink rule used in making the pattern was incorrect and differed from the actual shrinkage of the alloy used. Every alloy has slightly different shrinkage allowance requirements. As a result, the final Aluminum casting came out to be slightly bigger than the actual casting. The Shrinkage factors considered in the present pattern making were derived from a textbook because of which all the measurements of the casting were uniformly large in comparison to the actual sample part.

CHAPTER VII

SUMMARY AND CONCLUSION

7.1 Fused Deposition Modeling

FDM extrudes an ultra thin layer of thermoplastic filament from a spool. Actually, two filaments are extruded: one for the model and the other for the undercut/overhang support. FDM modeling materials include ABS investment casting wax, elastomer, polycarbonate, polyphenylsulfone, and durable polyester. The FDM office systems can make parts as large as 12 x 8 x 8 in. at a rate of 4 in./sec.; accuracy is ±0.013 in. The standalone machines can build models measuring 23.6 x 19.7 x 23.6 in. The accuracy of these models, when larger than 5 in., is ±0.0015 in./in.

When used for pattern production, FDM reduces the lead time from weeks to days while offering cost savings. An additional benefit when using FDM for sand casting patterns is that there is no change in tool design, the tool making process or the casting process. The benefits are delivered by simply replacing machining with FDM while retaining standard design practices and manufacturing procedures.



Figure 18 The FDM-ABS pattern as fabricated

7.2 Conclusion

The FDM-ABS (Acrylonitrile Butadiene Styrene) model is fabricated in Stratasys Dimension machine as shown Figure 17. The current ABS model held good tolerances with a maximum out of tolerance of 0.0068 inches (0.0016 in/in). The final casting had a maximum dimensional discrepancy in the x- dimension of 0.0132 inches (0.0028 in/in).

The surface finish suffered due to the pattern porosity, which allowed ceramic shell inclusion, sometimes completely through the thin planar sections of the component. Also, there was some shell cracking due to expansion of the material, which allowed some small “rat tails” in the casting where the molten metal flowed out into the cracks. Other than these problems, which could be corrected with pattern treatment, the majority of the surface finish was acceptable at 60 micro-inches.

By replacing machined patterns with FDM matchplates, companies can move from tool design to production sand castings in as little as one week. Since FDM is an automated, unattended process, sand casting foundries also increase overall efficiency and productivity while reducing labor costs.

Sand casting has been used for centuries with little change to the basic process. Today, the process can be improved with FDM, which enables high volume production and make low volume production of custom pieces feasible. Sand cast iron, steel, brass, bronze and aluminum parts can be produced in less time than previously possible.

It is concluded that in order to develop a bigger market for production grade tooling manufactured using layer manufacture techniques two things are required: technical developments, notably with regard to accuracy, surface finish, and durability; and an increased awareness of the economics of volume manufacture and of the importance of tooling within that economic framework.

The impact rapid prototyping (RP) can have on the design process and the product development process as a whole is demonstrated in this thesis. The speed and flexibility of RP technologies decreased the overall time to complete the new product.

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