

10-31-1992

Application of desktop manufacturing system (SLA) for the manufacturing of a centrifugal pump impeller using CAD (I-DEAS)

Wasimuddin Azam Muhammad Syed
New Jersey Institute of Technology

Follow this and additional works at: <https://digitalcommons.njit.edu/theses>



Part of the [Manufacturing Commons](#)

Recommended Citation

Syed, Wasimuddin Azam Muhammad, "Application of desktop manufacturing system (SLA) for the manufacturing of a centrifugal pump impeller using CAD (I-DEAS)" (1992). *Theses*. 2373.
<https://digitalcommons.njit.edu/theses/2373>

This Thesis is brought to you for free and open access by the Electronic Theses and Dissertations at Digital Commons @ NJIT. It has been accepted for inclusion in Theses by an authorized administrator of Digital Commons @ NJIT. For more information, please contact digitalcommons@njit.edu.

Copyright Warning & Restrictions

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specified conditions is that the photocopy or reproduction is not to be “used for any purpose other than private study, scholarship, or research.” If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of “fair use” that user may be liable for copyright infringement,

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

Please Note: The author retains the copyright while the New Jersey Institute of Technology reserves the right to distribute this thesis or dissertation

Printing note: If you do not wish to print this page, then select “Pages from: first page # to: last page #” on the print dialog screen

The Van Houten library has removed some of the personal information and all signatures from the approval page and biographical sketches of theses and dissertations in order to protect the identity of NJIT graduates and faculty.

ABSTRACT

Application of Desktop Manufacturing System (SLA) for the Manufacture of a Centrifugal pump Impeller using CAD (I-deas)

by

Wasimuddin Azam Muhammad Syed

Desktop Manufacturing (DTM) systems which combine personal computer, laser and other technologies are being used to sculpt objects from computer generated models created on computer aided design (CAD) workstations. As a member of DTM systems, StereoLithography Apparatus (SLA) transforms 3-dimensional designs into a 3-D output. This can substantially reduce the time required to produce a prototype through the process of photopolymerization. The process involves the transfer of a liquid plastic monomer into a solid polymer by exposing it to ultraviolet light.

Although the process looks productive, inefficiencies can occur, if incorrect parameters are selected before its application for a particular prototype fabrication. In understanding the correct requirements of the prototype being built, efficiency can be maximized by the use of desktop manufacturing systems.

**APPLICATION OF DESKTOP MANUFACTURING SYSTEM (SLA)
FOR THE MANUFACTURE OF A CENTRIFUGAL PUMP
IMPELLER USING CAD (I-DEAS)**

by

WASIMUDDIN AZAM MUHAMMAD SYED

**A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Manufacturing Engineering
October 1992**

APPROVAL PAGE

Application of Desktop Manufacturing System (SLA)
for the Manufacture of a Centrifugal pump
Impeller using CAD (I-deas)

by
Wasimuddin Azam Muhammad Syed

~~Dr. Steve Kotefski~~, Thesis Advisor
Assistant Professor
Department of Engineering Technology

Dr. Raj Sodhi, Committee Member
Director Manufacturing Engineering Program
Associate Professor
Department of Mechanical Engineering

Dr. Nouri Levy, Committee Member
Associate Professor
Department of Mechanical Engineering

BIOGRAPHICAL SKETCH

Author: Wasimuddin Azam Muhammad Syed

Degree: Master of Science in Manufacturing Engineering

Date: October, 1992

Date of Birth:

Place of Birth:

Undergraduate and Graduate Education:

- . Master of Science in Manufacturing Engineering, New Jersey Institute of Technology, Newark NJ, 1992.
- . Bachelor of Engineering in Mechanical Engineering, N.E.D University of Engineering and Technology, Karachi, Pakistan, 1990.

Major: Manufacturing Engineering

Professional Positions:

- . Teaching Assistant, January, 1992 - May, 1992, Department of Mechanical Engineering.
- . Trainee Engineer, August, 1990 - December, 1990, M & J Fabricators and Manufacturers Karachi, Pakistan.

**This thesis is dedicated to
my parents**

ACKNOWLEDGEMENT

The Author wishes to express his heartfelt gratitude to Dr. Steve Kotefski for his invaluable time and counsel, which made this thesis possible.

A special thanks to Dr. Raj Sodhi who most generously arranged the access to the apparatus.

He would like to appreciate Mr. Alan Bondhus and Mr. Thomas curry, without their help, completion of this thesis would have been difficult.

The author is also grateful to Mr. Ram Reddy for his continuous help in solving the I-DEAS problems.

A special appreciation is due to Mr. Azfar Ali for providing the necessary technical data of the pump impeller.

Finally a thank you to friends and a deep indebtedness for his family, specially to his mother, for her help, support, perseverance and inspiration during his studies.

TABLE OF CONTENTS

	Page
1 INTRODUCTION	1
2 INTRODUCTION TO COMPUTERS	4
2.1 Definition	4
2.2 Hardware	4
2.2.1 Central Processing Unit	6
2.2.1.1 Controller	6
2.2.1.2 Arithmetic and Logical Unit	8
2.2.1.3 Memory	9
2.2.2 Mass Storage Devices	10
2.2.2.1 Magnetic Tape	11
2.2.2.2 Magnetic Disk	12
2.2.2.3 Other Storage Devices	14
2.2.3 Input/Output Devices	15
2.2.3.1 Card Reader/Punch	15
2.2.3.2 Paper Tape Reader/Punch	16
2.2.3.3 Terminals	17
2.2.3.4 Printers	19
2.3 Categories of Computers	20
3 COMPUTER AIDED DESIGN AND MANUFACTURE	24
3.1 Introduction	24
3.2 A Brief History	25
3.3 New Developments	27
3.4 The Architecture of CAD/CAM	27

3.4.1	System Hardware	29
3.4.1.1	Graphics Input Devices	29
3.4.1.2	Graphics Display Devices	33
3.4.1.3	Graphics Output Devices	36
3.4.2	Operating System Software	37
3.4.3	Application Software	39
3.4.3.1	2-D Drawing	40
3.4.3.2	Basic 3-D Drawing	40
3.4.3.3	Sculptured-Surface Software	41
3.4.3.4	3-D Solid Modeling	42
3.4.3.5	Engineering Analysis	42
3.5	CAD System Examples	42
3.5.1	Catia	43
3.5.2	AutoCAD	44
3.6	Benefits of CAD/CAM	46
3.7	Applications of CAD/CAM	47
3.7.1	Aircraft Pilot Training	48
3.7.2	Electronics Industry	48
3.7.3	Finite Element Analysis	49
4	DESK TOP MANUFACTURING	51
4.1	What is Desktop Manufacturing	51
4.2	Rapid Prototyping Systems	54
4.2.1	StereoLithography	55
4.2.1.1	Photopolymers Used in SLA	60
4.2.1.2	Coordinate System Used in SLA	63
4.2.2	Selective Laser Sintering	65
4.2.2.1	Materials Used in SLS	67

4.2.3	Fused Deposition Modeling	68
4.2.3.1	Materials Used in FDM	70
4.2.3.2	Material Consumption	72
4.2.4	Laminated Object Manufacturing	72
4.2.5	Light Sculpting Process	76
4.2.6	Ballistic Particle Manufacturing Process .	77
4.2.7	Free Form Fabrication	78
4.2.8	Brute Force Imaging	81
5	DESIGN AND MANUFACTURE OF THE 3-D MODEL	84
5.1	Introduction	84
5.2	Facilities Available at NJIT	84
5.2.1	Computer System	85
5.2.1.1	Sun Workstations	85
5.2.1.2	Tektronix 4693DX Color Imager	85
5.2.2	I-DEAS Package	87
5.2.2.1	I-DEAS Basic Structure	87
5.2.2.2	I-DEAS Solid Modeling	88
5.2.3	StereoLithography Apparatus (SLA-250)	89
5.3	Steps Involved in Building the Part	90
5.3.1	CAD System Stage	90
5.3.2	SLA Stage	109
5.3.3	PCA Stage	116
6	APPLICATIONS AND BENEFITS OF DTM SYSTEMS	117
6.1	Applications	117
6.1.1	Design Engineering	117
6.1.2	Manufacturing Engineering Link	118
6.1.3	Concurrent Engineering	120

6.1.4	Applications of SLA	121
6.1.5	Applications of SLS	122
6.1.5.1	The SLS Process Applied to Investment Casting	123
6.1.6	Applications of FDM process	124
6.1.6.1	Casting Applications of FDM	124
6.2	Benefits	124
6.2.1	Design Optimization	124
6.2.2	Product Quality	125
6.2.3	Speed	125
6.2.4	Simple or Complex Part Manufacturing	126
6.2.5	Risk Reduction	126
6.2.6	Time to Market	127
6.2.7	Benefits to Investment Casters	127
6.2.7.1	Through SLS	127
6.2.7.2	Through FDM	127
7	ANALYSIS, COMPARISONS AND CONCLUSIONS	129
7.1	Experimental Analysis	129
7.1.1	Assumptions for the experiments	129
7.2	Analysis of Results Obtained	130
7.2.1	Process Comparison on the Basis of Cost ..	130
7.2.2	Process Comparison on the Basis of Time ..	135
7.2.3	Process Comparison on the Basis of Quantity	135
7.2.4	Process Comparison on the Basis of Complexity	135
7.3	Conclusions	142
7.4	Final Recommendations.....	143

APPENDIX 145
BIBLIOGRAPHY 147

List of Figures

Figure	Page
2.1	General organization of a simple computer system ... 5
2.2	Cathode ray tube (CRT) 18
3.1	CAD System Architecture 28
3.2	I/O peripherals of a CAD system 30
4.1	The Basic diagram of how StereoLithography works 56
4.2	Supports for Stereolithography process 62
4.3	Coordinate Systems 64
4.4	Selective Laser Sintering process 66
4.5	Fused Deposition Modeling (FDM) 69
4.6	Laminated Object Manufacturing process 73
4.7	View of the LOM process 75
4.8	Three-dimensional printing sequence used for rapid prototyping 79
5.1	Interactive Sun Microsystems, CAD workstation 86
5.2	The StereoLithography Process 91
5.3	Impeller Blade wire frame viewed from different angles 94
5.4	Impeller Blade profiles oriented to be skined 95
5.5	Skin grouped profiles of the impeller blade viewed from different angles 96
5.6	Blade skined solid model 97
5.7	Profile of the front Shroud 98
5.8	Profile of the Back shroud 99
5.9	Solid model of the impeller blade 100
5.10	Front Shroud Solid model 101

5.11	Back Shroud Solid model	102
5.12	Blades joined to back shroud	103
5.13	Pump Impeller wire frame	105
5.14	CAD Model in Positive X,Y,Z Octant	107
5.15	Object and Support positioned for efficient drainage	108
5.16	Basic Part Preparation Data Structure	110
5.17	Slice Process	112
5.18	The Merge Process	113
6.1	Cost of Design and Engineering Changes	119
7.1	Sand Casting Design Cycle of the centrifugal pump Impeller	131
7.2	DTM Design Cycle on SLA of Centrifugal Pump Impeller	132
7.3	Cost Comparison: Sand Casting vs SLA	134
7.4	Investment Casting Development Cycle: DTM System vs Conventional	137
7.5	Cost Quantity Comparison : SLA vs Conventional tooling	139
7.6	Technology Price Performance: DTM systems vs CNC .	141

List of Tables

Table	Page
4.1 Comparative chart of Specifications of DTM systems	83
7.1 Experimental data of centrifugal pump impeller for cost comparison of SLA vs Sand Casting	133
7.2 Investment casting development cycle data DTM vs conventional	136
7.3 Cost quantity comparison data SLA vs conventional tooling	138
7.4 Technology price performance data DTM systems vs CNC	140

CHAPTER 1

INTRODUCTION

In the nineteenth century, the industrial revolution considerably enhanced man's physical power. In the present century, a second industrial revolution is taking place, with computers offering an enhancement of man's mental capabilities. It is quite unthinkable these days to undertake a major engineering project without the use of a computer. More complex problems can be tackled with the computers now a days, and that more calculations can be performed in a given time. With the advent of VLSI, computer hardware is also getting smaller in size. Because of this size reduction and power, its applications are increasingly being spread to other areas of industry which formerly could not use the traditional computers owing to their cumbersome size.

As a result of these developments in computer science, computer aided design and computer aided manufacture (CAD/CAM) was conceived and is rapidly gaining acceptance in engineering industries for their ability to create major increase in productivity. Computer aided design is making a big impact in the industry and using the techniques, companies can now make and modify intricate drawings of potential products faster than ever.

Furthermore, computer-aided engineering (CAE) permits the prediction, with some degree of accuracy, of the

mechanical performance of those parts before they are made. Still many designers have trouble visualizing a part appearing on the screen or from a computer-generated drawing; they want a prototype that they can touch. However, prototyping, which involves model shop work and tooling costs thousands of dollars and months of time.

But now an emerging technology referred to as Rapid Prototyping, Free Form Manufacturing, or **Desk Top Manufacturing** systems-seized manufacturer's attention. Working from CAD data, these devices use various techniques and materials to build physical, 3D models before any money is spent on tooling. Desk Top Manufacturing systems are allowing companies to by-pass tooling and produce prototypes in minutes or hours rather than weeks or months.

The objective of this thesis was to study the applications of one of these latest techniques (SLA) to build prototypes of complex parts and analyze different parameters to evaluate the conditions ideal for the application of desktop manufacturing system. For the purpose, an actual working centrifugal pump impeller was selected. The reason for selection being the complication of its geometrical contours, which make the pump impossible to machine and difficult to cast. A company, actually took months to build the impeller prototype, spending thousands of dollars.

Using facilities available at NJIT, solid models were made on I-DEAS package, the files were then transferred to

the StereoLithography Apparatus (SLA-250) available at the campus. Thus building the prototype of the pump impeller in matter of hours. Then a set of experiments were performed evaluating the better conditions for the application of Desktop manufacturing system, in the manufacture of complex parts, using the results recommendations were made.

As Computers and Computer Aided Designing are the two basic requirements before using any Desktop Manufacturing system, those are explained in detail in the second and third chapters. The fourth chapter explains the different available Rapid Prototyping methods and the materials used in each of them. The fifth chapter includes the detailed procedural steps for constructing the prototype of the selected impeller, from CAD design to the final 3D model. In the sixth chapter applications and benefits of using the desktop manufacturing techniques were discussed. In the seventh and the final chapter, efforts were focused on analyzing the processes and evaluating a comparative result with the conventional prototype building methods. The data obtained during the experiment was used in making conclusions and recommending the better conditions for building a part according to different requirements.

CHAPTER 2

INTRODUCTION TO COMPUTERS

2.1 Definition

If the definition of a computer along with its basic concepts is neglected, one could not understand the principals on which DTM works. Therefore in order to have a solid base and a better understanding of DTM one must have a clear picture of the components used in it and computer is the base of all such systems.

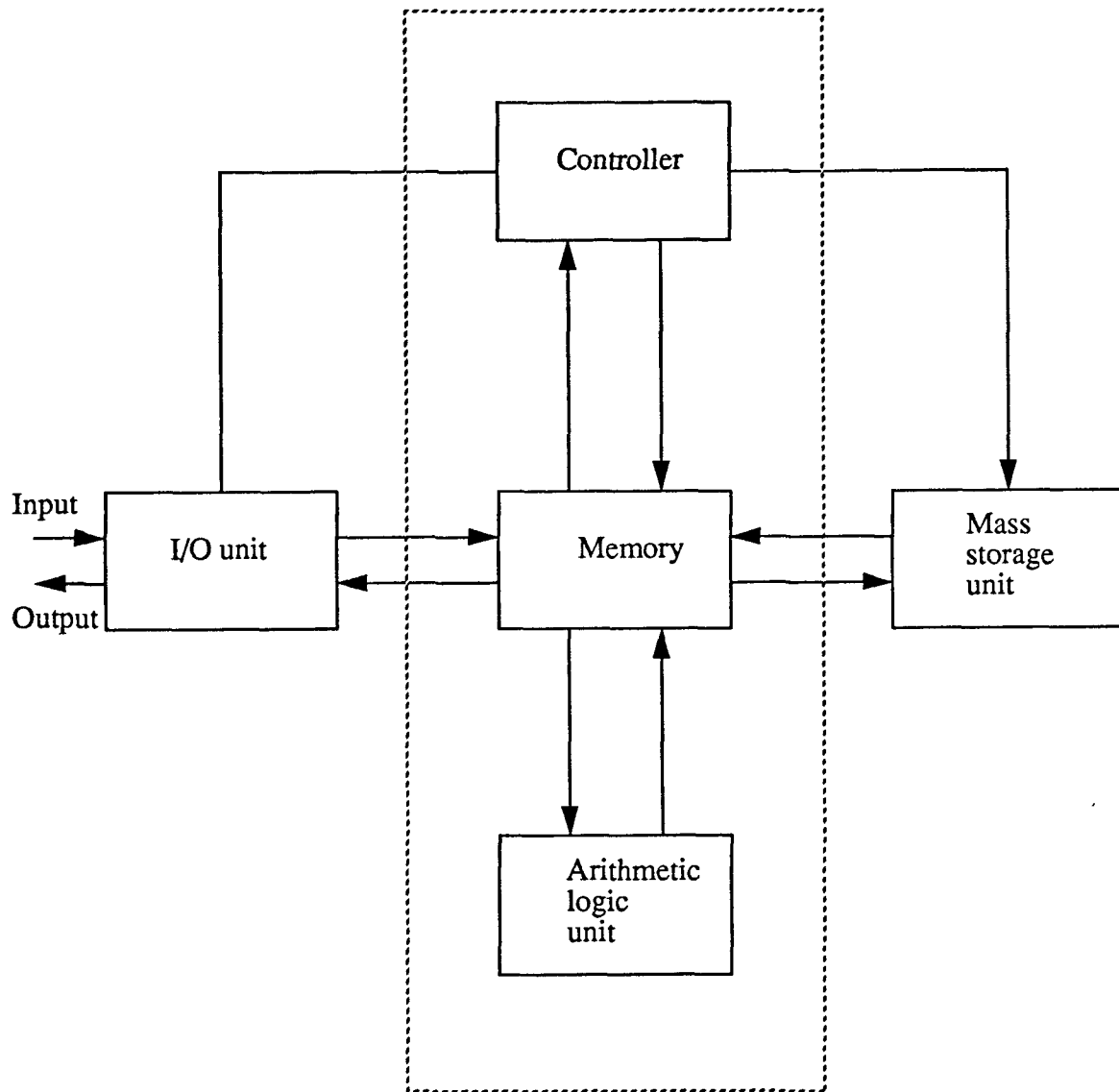
The digital computer is an electronic computing machine that can perform mathematical and logical operations and data processing functions according to a predefined series of instructions known as a program. The physical component units making up a computer system are often called the "hardware", whereas the programs are commonly referred to as the "software".

2.2 Hardware

The three main categories of hardware components are as follows:

- (i) Central processing unit (CPU)
- (ii) Mass storage devices.
- (iii) Input/Output (I/O) devices.

Figure 2.1 illustrates schematically the relationship between the above three main categories of computer hardware. The way in which these hardware components



General organization of a simple computer system

Figure: 2.1

are linked together defines the system architecture and thus influences its performance. The simple computer system as shown in fig. 2.1 can be expanded if necessary into a complex system with many input/output and mass storage devices. Indeed, it sometimes can even have more than one CPU to do processing in parallel, as in some multiple processor systems.

2.2.1 Central Processing Unit

The central processing unit is the nerve of any digital computer system, since it coordinates and controls the activities of all the other units and performs all the arithmetic and logical processes to be applied to data as specified by program instructions. The CPU can be considered as comprising three separate operating units :

- (a) controller
- (b) arithmetic and logical unit(ALU)
- (c) memory.

2.2.1.1 Controller

The controller basically acts as an administrator in a computer. It examines sequentially each individual instruction in the user's program, interprets it and decides how and when to perform the operation. It then informs the ALU what to do and where to obtain the necessary information. It knows when the ALU has completed a calculation, and it tells the ALU what to do with the

results and what to do next. The arithmetic and logical unit, as its name implies, deals with arithmetic and logical operations. It performs the actual work of computation and calculation such as additions and subtractions which are as fundamental to the functions of computers.

Both the controller and the ALU make use of registers to perform their functions. Computer registers are small memory units within the CPU that can receive, hold and transfer data. Each register contains binary cells to represent a binary digit, called a bit. The number of bits in the register constitutes the computer's word length which can indicate to a certain degree the processing capability of the computer. Different computers have different number of registers depending on the complexity of the architecture of their CPU. In general, these registers are arranged in such a way that they provide support for the CPU to carry out many of its processing operations. These registers can be classified according to their functions as follows:

a) Program counter

The program counter, sometimes referred to as control register, contains the address of the next instruction to be performed by the CPU.

b) Instruction register

This register stores the current instruction so that it can be translated into the corresponding machine code for the

CPU to perform the required operation.

c) Memory address register

The memory address register is used to hold the address of data stored in memory so that the CPU knows from this register where to fetch the required data for each instruction as almost every instruction involves some kind of operation on data.

d) Accumulator

An accumulator is a register used to temporarily store intermediate results from arithmetic or logical operations.

e) Status register

A status register is used to hold a status word which contains information about the conditions of the CPU such as the result of a logical instruction, overflow during an arithmetic operation, and the interrupt state, etc.

2.2.1.2 Arithmetic and logical unit

The ALU is a hardware unit that consists of some circuitry capable of carrying out arithmetic and logical functions that are specified in a program. Most ALUs can add and subtract, but there are now some ALUs that can perform multiplication and division, and even other complex mathematical functions.

2.2.1.3 Memory

The memory sometimes called main memory, of a computer contains binary storage units which are grouped into bytes of 8,16 and even 32 bit length. Then, a number of these bytes are organized into a word whose length depends on the design of the computer. A word is a unit of memory addressable by the CPU and it usually occupies one memory location. The main memory can store information such as program instructions to be executed by the controller and data to be processed by the ALU. This stored information is then made available as required for the use of either the controller, or the ALU, or other units within the computer. Intermediate results can also be stored in memory while the ALU is working on another part of the program. These stored partial answers may later be used to solve other sections of the program.

There are various types of storage medium used for the main memory of a computer. The most common type is the ferromagnetic core often referred as core storage. Core storage is non-volatile, so the data stored in it will not vanish when the power supply is interrupted.

Another common storage medium for computer main memory is the semiconductor storage which consists of electronic devices such as transistors. These transistor circuits are arranged into storage cells, also known as 'flip-flop', each of which represents a bit, as a core does in core storage. With the application of Large Scale Integration (LSI),

thousands of these transistor memory cells can be etched onto little chips of silicon less than 1/10th of an inch or may be less in size. Such a chip can easily contain more than 100 bits or more of main memory. However, this type of storage medium is volatile which means that the data in each cell will disappear as soon as the power is cut off.

2.2.2 Mass Storage Devices

As computers may often operate on an enormous amount of data that exceeds what it can hold at one time, backing store is commonly used to supplement the main memory and to save the data on a permanent basis. There are several types of devices that can provide backing storage, but the choice will mostly depend on how the information needs to be accessed. Generally two basic forms of backing store offering two different methods of access are available.

a) Sequential access storage

In this type of storage, also known as serial access storage, information can only be accessed in the same order that it is stored originally. All preceding items will have to be read when a particular piece of information is required or if any new information is to be written to a file.

b) Direct access storage

With direct access storage, individual items of information

can be located immediately for read or write without involving any other items in the file. As the information is literally available at random, that is, in any order, direct access storage is also commonly referred to as random access storage.

It is evident that the random access storage is much more efficient than the sequential access storage, therefore it is widely used for storing files that require frequent access where as sequential access storage is used mainly to store files as permanent records in an archive where they are very rarely accessed.

2.2.2.1 Magnetic tape

Magnetic tape is a storage medium similar to that used on a tape recorder except that its quality is superior and more durable. It is usually in the form continues strip of plastic material with a magnetic oxide coating on which data may be stored as a series of magnetized and non magnetized spots. Computer magnetic tape is commonly 1/2 inch wide and may be up to approximately 2,400 feet long wound on a reel, usually 8 to 12 inches in diameter. There are two main types of magnetic tapes, namely 7-track and 9-track. Most modern systems use 9-track magnetic tape because of its ability to store data at higher densities. Information can be recorded on magnetic tape in different densities typically 200, 556, 800 and 1,600 or even as dense as 6,250 bytes per inch (BPI). Magnetic tape speed ranges from 37.5 inches per

second to 200 inches per second, so the data transfer rate of the magnetic tape may vary from 7,500 BPI to 1,250,000 BPI.

The major advantages of magnetic tape are that it is relatively cheap when compared with other types of storage medium and that it can easily hold a large amount of data for its size. The capacity of a 450 ft reel may be up to 20 million characters or more. Magnetic tape, unlike punched paper tapes or cards, can be used again by simply overwriting previously stored data.

2.2.2.2 Magnetic disk

Magnetic disk is one of the most commonly used devices for direct access storage. A typical magnetic disk consists of six or more metallic platters that resemble gramophone records, except that the tracks are concentric instead of spiral. Each platter is coated on both surfaces with magnetizable material such as ferrous oxide. The platters are mounted about 1/2 inch apart on a spindle which rotates and spins the platters at speeds of 50 or more revolutions per second. Data are stored as series of magnetized or non magnetized spots on tracks on the platter surfaces, and are read or written as the platters rotate. Each track on a platter is further divided into sectors and information is accessed by track and sector address. On each standard-sized platter of 14 inches diameter, there may be as many as 256 tracks and 32 or more sectors per surface, so a platter can

easily hold thousands of characters, depending on the recording density which varies from 3,500 to 15,000 characters per track. As a result, a disk is potentially capable of storing as many as 20 to 1,000 M bytes of data. One M byte is equivalent to one million bytes and 1 K byte to one thousand bytes. The data transfer rate of disk storage is usually very high and ranges typically from 300,000 to 1.5 million bytes per second.

There are two types of magnetic disks :

(i) Floppy disk

In the early 1970s, a new disk storage device became commercially available for use as a low cost and faster alternative to storage on magnetic tape. The platter of this disk is coated with a layer of magnetic oxide much as in a conventional disk except that the platter is made of flexible plastic, hence this new disk is widely known as floppy or flexible disk. A floppy disk is a compact medium for random access backing storage, and it can be used for both input and output operations.

Floppy disks often come in three standard sizes: the largest is 8 inches in diameter, and the other smaller is 5 1/4 inches and the smallest one is the 3.5 inch in diameter. The storage capacity of all of these disks ranges from 125 K bytes to 1.44 M bytes depending on recording density and whether single sided or double-sided.

(ii) Winchester disk

The winchester disk is fairly recent development in disk storage technology. It has every thing similar to other disks except that the platter is coated with a lubricant to reduce friction between the read/write heads and the platter. It has a greater number of tracks as compared to the floppy disk.

There are several standard sizes of Winchester disks. The most commonly used ones are 5 1/4 inches, and 8 inches, but it can be as large as 14 inches. Typical storage capacity ranges from 10 M bytes to 200 M bytes in some latest microcomputers. Winchester disks are fast and reliable storage medium and are reasonably priced too, therefore they are often used to support the more powerful microcomputers as well as minicomputers, and are gradually taking over the position formerly held by floppy disks.

2.2.2.3 Other storage devices

As research and development into storage technology continues, new storage devices are coming in the market. These new devices include the Laser Beam Storage, Videodisc Memory Systems, Bubble Memory, and Electron Beam-Addressable Memory systems, all of which still in their childhood, potentially offer large storage capacity, faster access time and data transfer rate, and may become feasible alternatives to conventional magnetic memory technology in the future.

2.2.3 Input/Output Devices

Within the central processor of any computer, information can be processed at very high speeds, but before the central processor can be set to work, the data and programs must be entered into the computer memory. This is done by means of input devices which provide a vehicle for communications to the computer from the people who are concerned with its operation. Input devices are required to bridge the gap between the language of human beings and the internal code language of the relationships between numerals, characters and symbols, whereas within the internal store of a computer the various electronic circuits are able to respond only to patterns of electrical impulses. For communications in the opposite direction from the computer to the people, an output device is needed.

There are several types of input/output devices:

2.2.3.1 Card reader/punch

A card reader is an input device that transfers data from the punched card to the computer system. The reader is designed to read and interpret the codes on a card represented by the punched hole positions, and then generate electrical pulses that correspond to the sequences of bits which the computer can understand.

A card punch is an output device that transfers data from the computer system onto punched card. The punch outputs the

data as a pattern of rectangular holes in a card, and then reads it to verify that the card was punched correctly.

The standard punched card measures $7 \frac{3}{8}$ by $3 \frac{1}{4}$ inches and is 0.007 inch thick. The corners of a card may be rounded or square. A card is divided into 80 columns.

There is another type of machine, called keypunch, associated with punch cards. Keypunch contains a keyboard like an ordinary typewriter. Blank cards are entered into the keypunch machine, and a corresponding combination of holes are punched when a key is depressed. The cards are then read through a card reader to the computer.

2.2.3.2 Paper tape reader/punch

A paper tape reader operates in much the same way as a card reader. It translates the data punched in code on paper tape and transmits it into a central processing unit. The tape passes through a reader unit where the presence or absence of holes is detected and converted to electrical pulses.

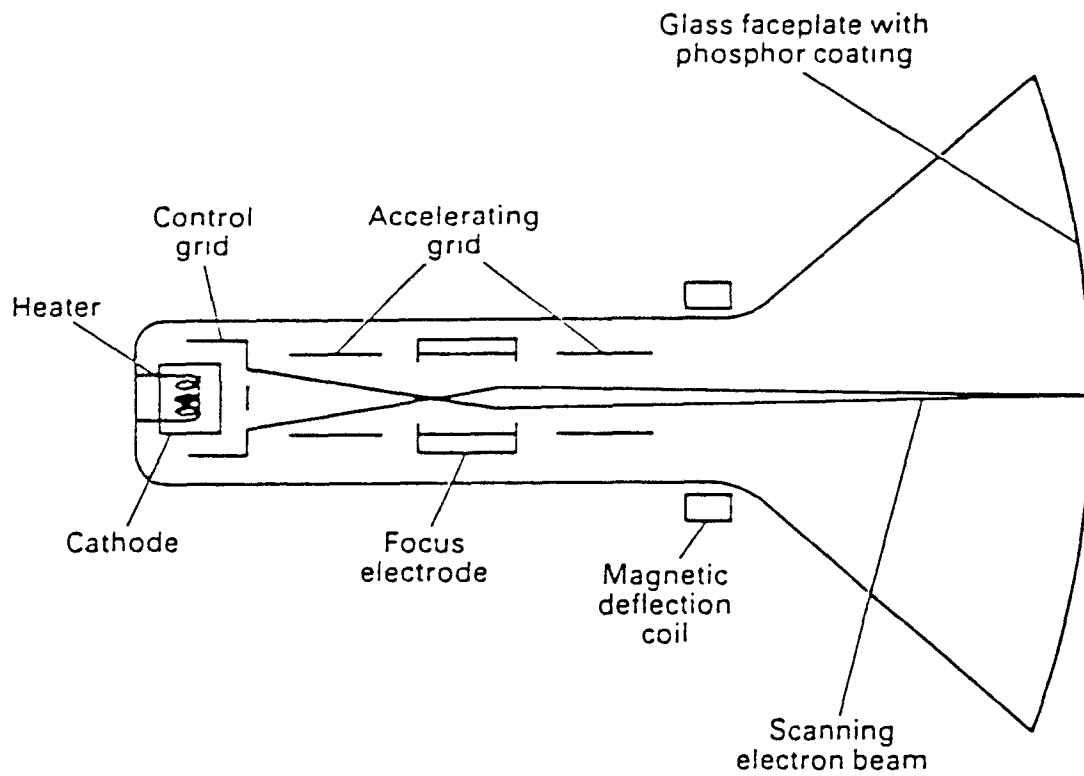
Paper tape, like a punched card is not commonly used these days as superior media for input, storage and output have become widely available. The major disadvantages of the paper tape are that errors are difficult to correct and that readers and punches are relatively slow, operating at approximately 500 and 300 characters per second respectively.

2.2.3.3 Terminals

There is a wide variety of terminal devices used in computer systems. One of the earliest types, the teletypewriter, also known as teleprinter, is usually an electro-mechanical or electronic device that resembles an ordinary typewriter in many ways except that it is connected directly to the computer via data communication lines. The unit works for both input and output, that is, the user can enter data or commands to the computer from the keyboard and may receive from the computer results or responses printed automatically on it.

As teletypewriter has mechanical parts, it can be quite noisy in an office environment when it is printing. Output from a teletypewriter is always printed on paper whether or not it is needed as a printed record or 'hard copy'. therefore it may unnecessarily use up paper and waste material resources. Other major disadvantages of the teletypewriter are its slow data communication rate and printing speed which limit significantly its use as a fast interactive terminal device with a computer.

Owing to the limitations of teletypewriter, a new generation of terminal devices, called visual display units(VDUs), has been developed. A VDU contains a keyboard and a display device which is usually a cathode ray tube (CRT) as shown in figure 2.2. The display device provide a screen to print information. Typically, a VDU is formatted to display 24 lines of 80 characters each.



- Cathode ray tube (CRT).

Figure: 2.2

Many VDUs widely used today are intelligent terminals with local memory and a local microprocessor. There are now some VDUs also in the market, built with touch-sensitive screens which enable data to be entered by touching the screen with the fingertip. These types of VDUs often have LCD (liquid crystal display) screens.

2.2.3.4 Printers

A printer is an output device that converts data from a computer and prints it in a readable form on paper. There are a number of different categories of printers used to produce printed output, such as:

- a) Line printers
- b) Serial printers
- c) Laserjet printers and paintjet printers.

a) Line printer

Line printer, prints a whole line at a time and operates on the same basic principle as a typewriter. It is usually a high speed printer, so it is very suitable for high volume output.

b) Serial printer

Serial printers, also known as character printers, are another category of printer which outputs one character at a time. In general a serial printer is much slower, but cheaper, than a line printer. The most common type of serial

printer is the dot matrix printer. The print head consists of a matrix of tiny needles, which hammers out characters in the form of patterns of small dots. Another type of serial printer is the daisywheel printer whose name originates from the fact that it uses a daisy-shaped disk made of plastic or metal which holds some 96 characters on its 'petals'. Print heads are interchangeable, so it is possible to use different character fonts. Daisy wheel printers can produce very good quality print and are widely used with word processing systems and other applications where print quality is important.

c) Laser printer

The laser printer is a relatively new technology in which a combination of electronics, lasers and copier techniques are used. An entire page of different size can be printed at one time by a laser printer. It is capable of producing very high quality print very quickly, and a wide selection of character fonts is available. Most laser printers work at speeds between that of dot matrix and daisy wheel printers.

2.3 CATEGORIES OF COMPUTERS

In the early 1960's there were only large and fast computers often called mainframes, which were expensive and had a high power consumption. As a result, only large institutions such as government departments, universities, and big commercial and industrial organizations could really afford to use

them. During the mid 60s, the market began to see the gradual arrival of the small computers known as minicomputers which satisfied to a certain extent the demand for low-cost computing. The appearance of these minicomputers heralded the ever-growing trend of miniaturization in computer technology that has currently reached the stage where a CPU, together with a large main memory and sophisticated input/output circuitry, can be squeezed onto a single LSI circuit chip of several millimeters square. Included, the design of many small computers, usually referred to as microcomputers, is based on these chips, together with some input and output devices.

Although the architecture of different types of computers is roughly the same, they can generally be classified as follows, according to their word length which represents the width of the internal data transfer paths of the computer.

- (a) The mainframe computer.
- (b) The minicomputer.
- (c) The microcomputer.

In general, the mainframe computer has a word length of 32 bits or more, and is the most powerful of the three categories in many ways. The minicomputer usually has a word length of 16 bits where as the microcomputer has a word length of 8 bits and is the smallest of the three categories. However, this classification of computers is gradually becoming more difficult as new minicomputers and

microcomputers are developed and introduced on the market. The 16-bit microcomputer, often called the supermicro, has already been with us for some time, and the 32-bit microcomputer, referred to as the megamicro, has also been launched in the market. With regard to the mini computer, a 32-bit machine known as supermini has been in production for several years. Thus, it can be imagined that the division of different categories of computers is not so clear-cut now as new computers become available and their capabilities overlap those of other categories.

As large mainframe computers and large minicomputers are capable of fast processing and have large main memory, they are commonly used to solve complex engineering and scientific problems such as iterative calculations in heat transfer analysis, structural design analysis, or fluid dynamics analysis. In a commercial environment, they are often employed in large-scale data processing operations such as payroll and corporate accounting, production scheduling, stock control, and maintenance of large information databases.

Small minicomputers and microcomputers are obviously less powerful than large mainframe computers and large minicomputers; but, because they are inexpensive, they become very cost-effective in some commercial and industrial applications. Another advantage is that they are small in size, so they are commonly used as a part of some large test equipment, or as the processor of a computer numerical

control machine tool, etc. Their applications are numerous, but generally they perform a small specific task within a large overall system for a particular function.

CHAPTER 3

COMPUTER AIDED DESIGN AND MANUFACTURE

Desk Top Manufacturing techniques became possible only because of the knowledge of CAD and CAM, therefore it looks necessary to explain the terms, before going in details of the topic.

3.1 INTRODUCTION

Computer-aided design (CAD) and computer-aided manufacturing (CAM) can be very simply defined, as its name implies, as the use of computers to aid the design and manufacture process. To explain more clearly, CAD/CAM is concerned with the application of computers to the manufacture of engineering components starting from the drawing office, to the production department, to the machine and assembly shops, to the quality control department, right through to the finished parts store. The technology of CAD/CAM represents an efficient, Accurate and consistent method to design and manufacture high-quality products. CAD/CAM involves two separate disciplines called Computer-Aided Design (CAD) and Computer-Aided Manufacture (CAM) that were originally developed independently over the past thirty years. They are now being combined into integrated CAD/CAM systems, with which a design can be developed and the manufacturing process can be monitored and controlled from start to finish with a single system.

3.2 A Brief History

CAD is a product of the computer era. Its development originated from early computer systems. CAD can trace its origin to the development of interactive computer graphic systems. The Sage project at Massachusetts Institute of Technology (MIT) was aimed at developing CRT displays and operating systems. A system called Sketchpad (Sutherland, 1963) was developed under the Sage Project. A CRT display and light pen input were used to interact with the system. This later, X-Y plotters were used as the standard hard-copy output device for computer graphics. An interesting note is that an X-Y plotter has the same basic structure as an NC drilling machine except that a pen is substituted for the tool on the NC spindle.

In the beginning, CAD systems were no more than graphics editors with some built-in design symbols. The geometry available to the user was limited to lines, circular arcs, and the combination of the two. The development of free-form curves and surfaces, such as Coon's patch, Ferguson's patch, Bezier's patch, and B-Spline enables a CAD system to be used for sophisticated curves and surfaces design. Three-dimensional model (model is the data abstraction in a computer) contains enough information for NC cutter-path programming, the linkage between CAD and NC can be developed. So called turn-key CAD/CAM systems were developed based on this concept and became popular in 1970s and 1980s.

The 1970s marked the beginning of a new era in CAD, the invention of three-dimensional solid modeling. In the past, three-dimensional wire-frame models represented an object only by its bounding edges. They are ambiguous in the sense that several interpretations might be possible for a single model. There is also no way to find the volumetric information of a model. Solid models contain complete information; therefore, not only can they be used to produce engineering drawings, but engineering analysis can be performed on the same model as well.

The initial developments of CAM were being made mainly in numerical control. Until recently, NC instructions had still to be produced and verified by hand. Now, CAM systems can automatically generate NC programs, and simulate tool paths quickly on graphics display for verification. In addition, most systems also have full process planning features for determining sequences of fabrication steps, and they may even have factory management capabilities for directing the flow of work and materials through the factory. The latest feature incorporated into CAM is robotics in which automated manipulator arms handle workpieces and tools.

3.3 New Developments

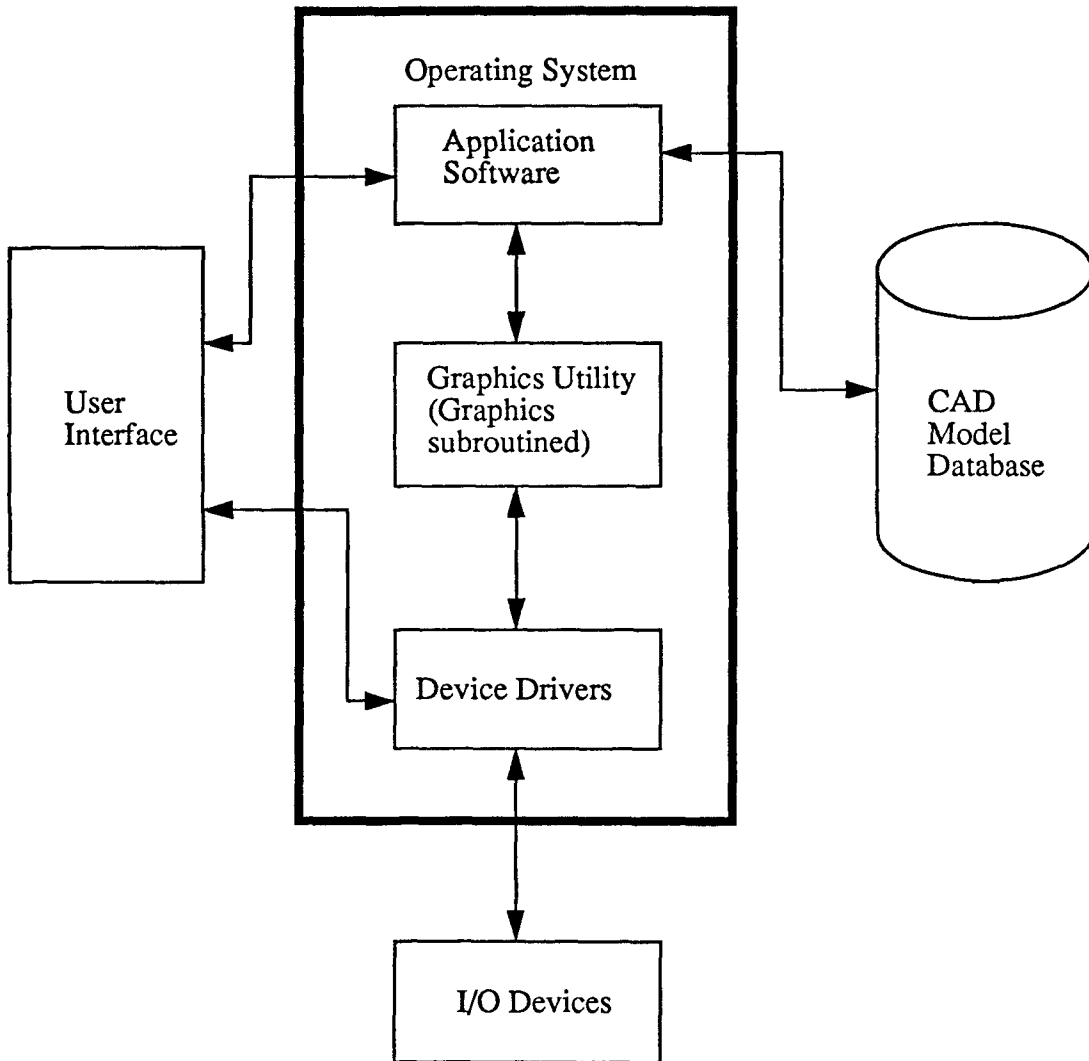
Today there are two developments in CAD. They are the implementation of CAD on personal computers (PCs) and the study of Artificial Intelligence (AI) applications in CAD. The first development has made CAD available and affordable. CAD used to be a tool used only by aerospace industries and other major industrial corporations. The introduction of PC CAD, such as, AutoCAD, VersaCAD, CADKEY, etc., has made it possible for small companies and even individuals to own and to use CAD systems. By 1988, more than 100,000 PC CAD packages have been sold. Although there are PC-based solid modelers, the majority of PC CAD systems are drafting and/or 3-D wire frame systems. Because rapid developments in microcomputers are enabling PCs to carry the heavy computational load necessary for solid modeling, we can expect many solid modelers running on PCs in the near future.

The linkage of AI and CAD is still in the research stage. The use of AI with CAD ultimately help to achieve the goal of design automation. In the near term, AI will be used to assist designers to find design parameters and to evaluate designs. In the long run, AI techniques will help simplify the design task.

3.4 The Architecture of CAD/CAM

A CAD/CAM system consists of three major parts (figure 3.1):

1. hardware: computer and input/output (I/O) devices;



CAD System Architecture

Figure: 3.1

2. operating system software; and
3. application software: CAD/CAM package.

3.4.1 System Hardware

In CAD/CAM, some special input/output devices are needed for it to perform the required functions, besides the usual hardware such as the CPU, mass storage devices, printer and alphanumeric terminal devices that can be expected to be found in a computer system. As computer graphics is a function fundamental to CAD/CAM, the special input/output hardware is mainly graphics devices that enable coordinate data to be input and allow graphical information or pictures to be displayed on a screen. Then, if it is required, hard copy of graphical data may be produced.

Figure 3.2 shows the typical devices used in a CAD/CAM system. Input devices are generally used to transfer information from a human or storage medium to a computer where "CAD/CAM functions" are carried out.

3.4.1.1 Graphics Input Devices

(i) Keyboard devices

Keyboards, buttons and switches constitute an important class of input devices that can be used in various configurations to meet different requirements. A keyboard

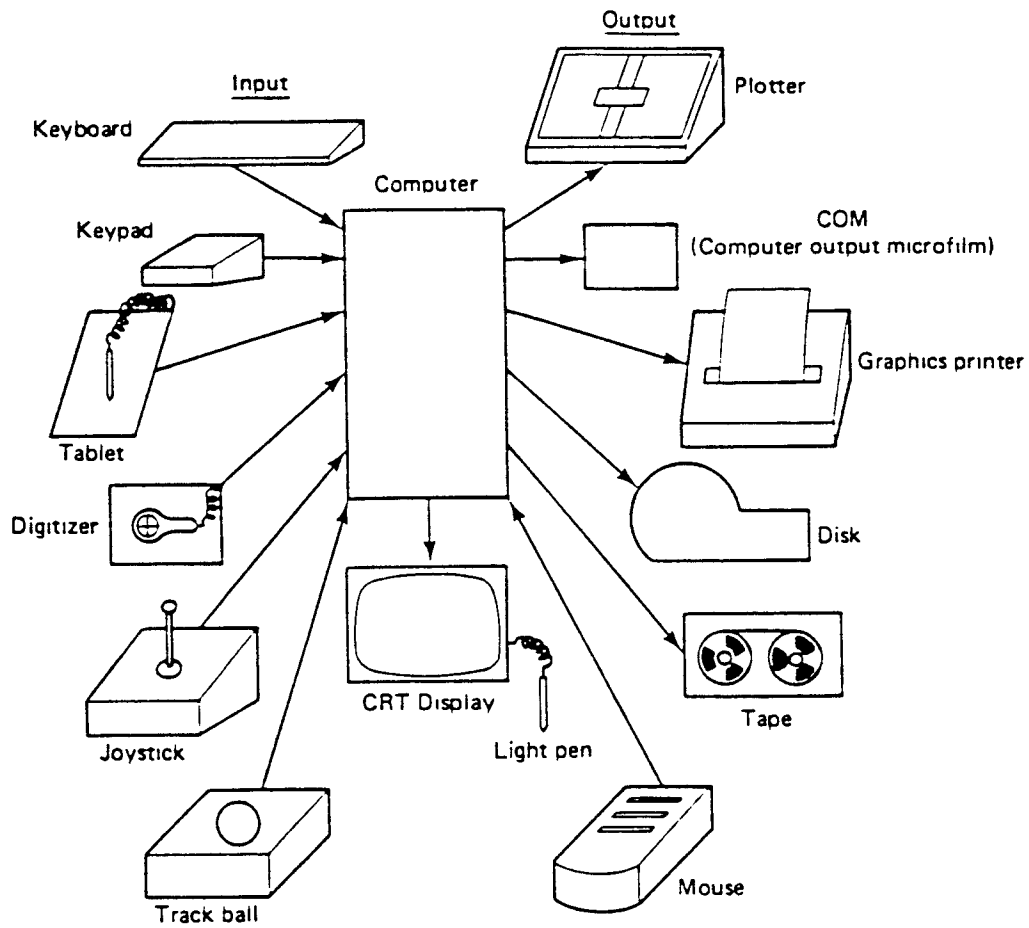


Figure: 3.2

inputs alphabets, numerals, and other characters by sending digital codes to the computer. A button, considered as a special type of momentary switch which rebounds after being depressed, can indicate only one data item, that is, the condition that it has been pressed. Similarly a switch can send only one piece of information to the computer, that is, whether its current position is on or off. The interpretation of the meanings of the button and switch input data is performed by the graphics software. A voice data entry system may also be considered as keyboard device that inputs complete words or phrases from a limited vocabulary by recognizing human speech.

(ii) Light-pens

Physically a light pen is very similar to the fountain pen in both size and shape, but its function is entirely different from that of a fountain pen. A light pen detects light on the CRT screen by some form of optical sensor. It can also be used for interactive graphics (locational information is fed back discretely to the computer). A light pen picks up items directly from the screen. It has been used since the beginning of interactive computer graphics. However, since it has to be used directly on the screen, the user must hold the pen in an elevated position. This can be tiring after an extended period of time.

(iii) Analogue devices

Many of the graphics input devices are analogue-to-digital (A/D) converters, which are essentially devices that detect some physical quantity such as speed, acceleration, force, position, direction, rotation, distance, etc., and then translate it into a numeric quantity such as a binary value that the computer can accept and understand. Some examples of these analogue graphics input devices are the digitizer, tablet, joystick, trackball, and dial.

a) Digitizer

A common way to take x, y coordinates off a drawing is to use a digitizer. The digitizer consists of a table or board similar to a drawing board, and a probe consisting of a pen or cursor which can be moved over the surface. The pen, or cursor, contains a switch that enables the user to register x, y coordinates at any desired position. These coordinates can be fed directly to a computer or to some off-line storage device such as industrial compatible magnetic tape.

b) Tablet

The tablet is a small low-resolution digitizer. It is often used as an alternative to the light-pen or in association with storage tube displays. The tablet serves as a surface corresponding to the CRT but remote from it. The user writes on the surface of the tablet, and the position of the pen is transmitted to the computer. The tablet is particularly

suitable for interactive design since it allows the designer to work naturally with a pen in his hand while watching the screen to check his actions.

c) Joystick, tracker ball and dial

Joystick, tracker ball and dial can play the same role as a light-pen in a CAD system, that is, they are used mainly for cursor control. A joystick allows the user to indicate the direction, speed and duration of the cursor motion.

A tracker ball is a simple rotating sphere operated with the palm of the hand. About one third of the ball is exposed through the top of the box. Cursor movement is controlled by the rotation of the ball. The distance that the cursor travels on the screen is directly proportional to the number of revolutions of the ball, whereas the direction of cursor motion corresponds to the direction of rotation.

A dial is one-axis cursor control device. A familiar example of the dial is the thumbwheel. Thumbwheels are most suitable for fast and accurate cursor movement along straight lines, but are not so desirable as a joystick or tracker ball for directing the cursor in a diagonal direction or along a curved path.

3.4.1.2 Graphics Display Devices

The graphic display screen is the most prominent piece of equipment in a CAD system because the main purpose of a CAD system is to display a computer-generated picture of a

design model on a screen so that it can be examined and graphically manipulated according to the operator's commands to make modifications. Nearly all graphics display devices are based on the cathode ray tube, although some are plasma panel displays.

CRT displays

In a CRT display, a heated cathode emits a continuous, high speed stream of electrons, which are formed into a beam by an aperture in a control grid surrounding the cathode. The electrons are then accelerated and focused to a point on the display surface. The electron beam is rapidly swept across the phosphor-coated face of the tube line-by-line. The beam current is regulated to increase or decrease its intensity in order that brighter or darker points are created along each swept line.

The two major techniques of generating an image are stroke-writing and raster scan. A stroke-writing device draws vectors or lines to create an image, while a raster scan device uses a matrix of closely spaced dots to form a picture.

Three main categories of CRT graphics displays are commonly used in CAD systems: direct-view storage tube (DVST), directed-beam refresh tube (DBRT), and refreshed raster scan display. Each of these CRT displays employs a combination of techniques to generate and maintain a picture on a screen.

i) Stroke-writing displays

A stroke-writing CRT display uses an electron beam to create a line image on a screen by making one line at a time.

Direct-view storage tubes and directed-beam refresh tubes come into the category of stroke-writing displays which are sometimes identified as calligraphic, random scan, vector writing, line drawing, etc.

a) Direct-view storage tube (DVST)

The most common DVSTs are manufactured by Tektronix company and became so popular that it is a de facto standard for graphics displays, against which the performance features of other display devices are judged.

b) Direct-beam refresh tube (DBRT)

The DBRT, like DVST, is a stroke-writing and refresh display device, except that the image is not stored and has to be continually refreshed in order to maintain it in a stable and flicker-free condition.

ii) Raster scan displays

In a raster scan display, the viewing screen is divided into a large number of tiny phosphor picture elements, often referred to as pixels. They are arranged into a matrix, called a raster, that represents the display area of the screen.

As raster scan display (most personal computers use raster-scan display) is a refreshed device, the image is regenerated at very frequent intervals, but this necessitates the image to be stored in some memory so that it can be obtained for the purpose of refreshing.

When compared with DVST and DBRT, the resolution of the raster scan display is relatively low, therefore diagonal lines appear jagged, like staircases. To tackle this problem, a technique, called anti-aliasing, effectively blurs the image so that its edges gradually change from one color to another.

Some advantages of the raster-scan display include: (1) a more continuous picture tone can be generated, and (2) the cost is usually lower than for random-scanning displays.

3.4.1.3 Graphics Output Devices

After a design has been finalized on the screen, a hard copy is often produced as a record of the design for presentation. To produce such hard copy output for a CAD system a plotter is generally used. Two main classes of plotters are commonly used in CAD system:

(i) Pen plotters

Pen plotters are the most popular kind of graphics output devices because of their versatility; they may be subdivided into flatbed plotter, drum plotter, beltbed plotter and plot-back digitizer.

The advantage of a pen plotter is that it can produce a very accurate drawing and in a flatbed type pen plotter a drawing can be seen while its being drawn.

(ii) Electrostatic plotters

Although a pen plotter can produce highly accurate drawings, the time it takes to plot a drawing is usually quite long because it can plot only line by line and only in the order that the data were entered. There is some unnecessary random pen movement also. In applications where high volume of graphics output is required within a short time, an electrostatic plotter is often used.

An electrostatic plotter, consists of an electronic matrix which can print dots onto charge-sensitive paper. Compared to pen plotters, electrostatic plotters can plot much more quickly, sometimes of the order of three to four times more quickly, but it is five times more expensive and the quality of the drawing is on average not as good, though acceptable, because it is a raster format output. The electrostatic plotter can also be used as a printer to output alphanumeric text.

3.4.2 Operating System Software

The operating system software is the interface between the CAD application software and the hardware. It may be defined as a program which organizes a collection of hardware into a consistent and coherent entity so that it can be used for

developing and running programs. It can assist users and their programs to make the most efficient use of system resources such as memory capacity and processing power with minimal programming effort for providing software to supplement and enhance the system facilities available.

In general, an operating system is usually provided with the computer by the vendor as a complete package, so there is no need for the user to write it. There are numerous different types of operating systems. Most of them are interactive, which means that a command entered by a user is executed immediately and the results are returned as soon as possible. Some sophisticated operating systems provide multi-user and multi-tasking capabilities which allow more than one user to access the system and more than one program to run in the system. Typically, no matter which type of operating system is used, it will invariably have utility programs such as an editor, an assembler and a compiler for some high-level programming language. These are the most basic facilities needed to develop a program. An editor enables a user to create and modify source programs which are just ASCII characters representing instructions in some programming language. An assembler is used to assemble programs written in the system's assembly language into binary code before they can be executed. A compiler serves essentially the same function as an assembler, but for programs written in a high-level language such as FORTRAN or PASCAL. Very often, an operating system provides a system

library which contains subroutines to perform basic functions such as input/output and file handling etc.

3.4.3 Application Software

CAD PACKAGE

CAD software is what gives a CAD system its functionality and personality. Software can be classified based on the technology used :

1. 2-D drawing
2. Basic 3-D drawing
3. Sculptured surfaces
4. 3-D solid modeling
5. Engineering analysis

Some of the commonly available functions provided by CAD software are

- * Picture manipulation : add, delete, and modify geometry and text
- * Display transformation : scaling, rotation, pan, zoom, and partial erasing
- * Drafting symbols : standard drafting symbols
- * Printing control: output device selection, configuration, and control
- * operator aid : screen menus, tablet overlay, function keys
- * File management : create, delete, and merge picture files

3.4.3.1 2-D Drawing

Two dimensional (2-D) drawing systems correspond directly to traditional engineering drawings. Basically, they are designed as a substitute for manual drafting. Some applications of 2-D drawing systems include:

- a) Mechanical part drawing
- b) Wiring diagram
- c) Printing circuit board design and layout
- d) Pattern nesting (sheet metal and garment)
- e) Facilities layout
- f) Architectural design and construction engineering
- g) Graphics art, technical publication
- h) Cartography

Nearly all CAD systems support 2-D drawing in one way or another. Even 3-D systems usually can produce 2-D drawings from their 3-D database.

3.4.3.2 Basic 3-D drawing

Basic 3-D drawing systems include 3-D wire frame, 2 1/2-D drawing, and cartography. A 3-D wire-frame model describes the edges and outlines of curves. A 2 1/2-D model is a 2-D model with a constant Z-axis dimension. Some cartography models can use digitized terrain data to produce contour and/or 3-D drawings.

There are some limitations of 3-D drawings, despite of those limitations, 3-D wire frame models are useful for many applications. Some include :

MECHANICAL ENGINEERING

- a) Part design
- b) Assembly design
- c) NC tool path
- d) Robot programming

ARCHITECTURAL ENGINEERING AND CONSTRUCTION

- a) Building design
- b) Structural analysis
- c) Piping layout and analysis

ELECTRICAL AND ELECTRONIC ENGINEERING

- a) Integrated-circuit (IC) chip layout
- b) Printed-circuit-board layout

CARTOGRAPHY

- a) Map preparation

3.4.3.3 Sculptured-Surfaces Software

It is the class of surfaces which is not analytical and does not include basic 3-D model geometries. Many applications require modeling of such surfaces such as

- a) Die design and manufacturing
- b) Automobile, ship and aircraft body design
- c) commercial and artwork

Many attempts are being made to put sculptured-surfaces models together with other types of models.

3.4.3.4 3-D Solid Modeling

There are six different types of solid representation schemes:

- i) Primitive instancing
- ii) Spatial occupancy enumeration(SOE)
- iii) Cell decomposition
- iv) Constructive solid geometry (CSG)
- v) Boundary representation (B-rep)
- vi) Sweeping

3.4.3.5 Engineering Analysis

Engineering analysis commonly conducted on a design include finite-element analysis (FEA), volume and weight calculations, kinematic simulation, and circuit analysis and simulation. The most widely used is finite element analysis, widely used in the following:

- a) Static and dynamic analysis of complex structures such as aircraft, bridges, buildings, cars, dams etc.
- b) Fluid flow, diffusion and consolidation problems
- c) Lubrication problems
- d) Heat conduction and thermal stresses

3.5 CAD System Examples

There are many CAD systems available in the market, out of which, two are explained as under:

3.5.1 Catia

It is a mainframe based CAD/CAM system marketed by IBM. It consists of a base module, which provides the basic interactive graphics functions, and several application modules. The application modules include:

- * 3-D design: for 3-D design.
- * Drafting: for drafting.
- * Advanced surfaces: for sculptured-surfaces design.
- * Solid geometry: for solid geometry design.
- * Kinematics: for kinematics simulation.
- * Building design: for architectural design.
- * Library: for custom symbols and objects define, storage, and classify.
- * Numerical control: for NC part programming.
- * Robotics: for design, simulation, and programming robot cells.

A common database is shared among all applications. Preprocessors and postprocessors are available to translate between CATIA and IGES (Initial Graphics Exchange Specification) data format.

CATIA runs on IBM 308X, 303X, and 43XX type computers under the VM/CMS operating system. It can be configured either with one terminal or two terminals per work station. When two terminals are used, one is used as alphanumeric terminal and the other one for graphics display. A processor associated with the terminal is used to relieve the central processor of display transformations, coloring, and shading.

The design data are organized into projects, models sheets, and libraries. With this organization, a large design project can be managed effectively. A layer filter can be used to display or plot one or many element layers simultaneously so that parts can be displayed selectively. Dimensions can be added to the drawings automatically.

Multiple-screen windows can be opened to allow the user to work on different views or different elements at the same time. On-screen window menus display frequently used commands. The user can use a programmable functional keyboard, a regular keyboard, or a tablet to enter commands.

A dial device with eight dials can perform dynamic coordinate transformations. Picture on the screen can be rotated, scaled, and panned dynamically through the dials. A local graphics processor associated with the workstation handles the transformation tasks.

3.5.2 AutoCAD

AutoCAD is a computer-aided drafting and design system implemented on a personal computer. Although AutoCAD is used in engineering workstations such as Sun, Apollo Domain, and IBM PC RT, the majority of AutoCAD implementations are still based on IBM personal computers and MS DOS-based machines. AutoCAD supports a large number of I/O devices. Since IBM PC and PC-compatible computers are generally available in the workplace, AutoCAD is a low cost yet effective solution to many CAD needs.

AutoCAD supports 2-D drafting and 3-D wire-frame models. The system is designed as a single user CAD package. The basic drawing elements are lines, polylines of any width, arcs circles, faces, and solids. Annotation and dimensioning are also supported. A variety of fonts and styles are available for text and dimension symbols. For 3-D objects an isometric display with a grid assists the user to lay out the design.

A group of geometric entities and texts can be selected and placed into position. The user can pick an entity or entities and define them as a group. By specifying a transformations, such as zoom, pan, move, rotate, etc., can be used to manipulate a drawing or part of it. An unlimited number of user-definable layers can be used, each layer can be displayed and plotted with different colors and line types.

An embedded language, AutoLisp, is available to those wanting to customize their systems.

There are many other software packages that can be added onto the Auto-CAD system. AutoCAD has been used for all kinds of two-dimensional applications. A standard drawing interchange file format, DXF, is used. Users can develop application programs around the system. IGES processors and postprocessors are also available to transfer data to and from other CAD systems.

3.6 Benefits of CAD/CAM

It is rather difficult to outline all the possible benefits and advantages of using CAD/CAM, but it can be easily imagined that they are considerable in terms of working efficiency and productivity alone. CAD can drastically reduce the number of steps involved in the design process for a particular product and can also make each design step much easier and less tedious for the designer to perform. As a result, an immense increase in the work output of a designer can be made possible and an enormous amount of time-saving can also be achieved between the initial conception of an idea and its final implementation as a product design. CAD enables an accurate representation of a design and provides the designer with a versatile tool to graphically manipulate it. With this, the designer can easily obtain a deep insight into complex problems arising from the design. This will help the designer make better decisions and will reduce the possibility of having errors which may be difficult to spot by any other method. Hence the designer is more likely to arrive at an optimal solution which will eventually lead to an improved quality product making a more competitive stand in the market.

CAM can greatly increase productivity on the shop floor in various ways. It can automatically generate NC programs and generates them with fewer errors as they can be checked on a graphics display. With CAM, scheduling of components and tools through manufacturing workstations is made much

easier. As a result of these, delivery times of products are remarkably reduced.

As far as management is concerned, CAD/CAM can improve capacity planning and production scheduling. thus better inventory control can be achieved, and the working capital required by the company is reduced. It is also possible to simplify product forecasting, estimating and price-fixing, so that the process of preparing tenders is made much easier and is greatly speeded up.

Finally, one other benefit of CAD/CAM, which I think is crucial to its success, is that as all information is stored in the computer instead of on paper; the transfer of data from department to department is quicker, more reliable and less redundant.

3.7 Applications of CAD/CAM

Interactive computer graphics has been widely applied in many different areas of science and technology where drawings of any kind are a vital element for illustrating new scientific or design ideas to another person. Its applications include study of molecular structures in chemistry, medical research, animation, aircraft flight simulation, structural design in aircraft, shipbuilding and automobile industries, integrated circuits and printed circuit board design in the electronics industry, town planning and architectural design, pipe routing and layout

in chemical plant design, mesh data preparation for finite element analysis and draughting, etc.

3.7.1 Aircraft Pilot Training

Nowadays, aircraft pilots are trained on flight simulators instead of a real aircraft. A flight simulator contains all the usual instrumentations and television screens showing computer-generated views of the terrain on takeoff and touchdown. These views changes instantaneously according to the actions taken by the trainee pilot providing him a precise impression of the aircraft's motion. The major advantages of using flight simulators are the cost savings on fuel, better safety and the ability to prepare the trainee pilot to fly an aircraft to numerous airports all over the world.

3.7.2 Electronics Industry

The electronics industry also extensively uses interactive computer graphics in the design of integrated electronic circuits. It may take a human being weeks to draw such complex circuit diagrams by hand, which if interactive computer graphics system is used, can be drawn in a much shorter time with the possibility of correcting any ambiguity and inconsistency in the design. this latest development in integrated circuit design has contributed enormously to the trend towards low-cost electronic equipment.

3.7.3 Finite Element Analysis

Finite element analysis is an important engineering technique for carrying out stress analysis on many types of structures. This powerful technique is applied in nearly all fields of engineering, as well as to reactor physics, because it offers the designer a potent and effective computational tool for analyzing complex engineering structures. However, the finite element method is often not easy to use, but the use of CAD system in data preparation process has reduced most of the problems.

In draughting, computer-aided design is now very commonly used to ease the task of the draughtsman as well as to help increase his efficiency. The draughtsman need not manually draw each line in an engineering drawing. Rather, the CAD system construct the lines, circles or almost any shape required. Other automatic features provide additional draughting aids like auto scaling and dimensioning facility. When the drawing is complete copies may be produced automatically in any desired number. This shows that the CAD systems can greatly improve the production of drawings in terms of both quality and speed.

Apart from the previous examples, CAD/CAM is used in various degree in many other branches of science and technology which are just too numerous to mention here. However, CAD/CAM has been applied extensively to mechanical engineering and manufacturing industries.

At present integrated CAD/CAM systems are mainly used in problems involving surface definition, particularly in aircraft industry. These problems are often so complex and produce difficulties in handling very large quantities of data for both design and manufacture that computerized methods are essential.

Less sophisticated industries than the aircraft industries are now also starting to use CAD/CAM systems. Many research institutes have investigated methods for integrating CAD and CAM by linking the geometry-descriptive part of CAD with the manufacturing technology of CAM and CNC. The integration of CAD with the desktop manufacturing techniques is also under research, and would be the target for rest of this thesis.

CHAPTER 4

DESK TOP MANUFACTURING

Most engineers use models, or prototypes, to test designs. In some industries, such as automotive and aerospace, these models are expensive to make because they require expensive tooling and lengthy manufacturing cycles. Computer aided techniques such as FEA and solid models let engineers bypass some of the time and expense, but wouldn't it be nice if we could reach into the screen and take the part in our hand? Technology is emerging to let designers do just that.

Today with the advent of Desktop Manufacturing systems it looks possible to have a hands on model of a part within hours instead of weeks at reasonable costs. Prototype parts can be made from plastics or with laminates, paper and other materials. The technology produces parts considerably faster and greater complexity and size than can be done with machine tools.

4.1 What is Desktop Manufacturing

The easiest way to describe desktop manufacturing is with an analogy to desktop publishing. The 1980s saw the emergence of desktop publishing. With desktop publishing, graphics software and a laser printers are used to turn a standard text file into a close likeness of a typeset page. For many purposes, this likeness serves just as well as a typeset document and offers the creator substantial savings in cost

and time. What's more, the quality of a document created with desktop publishing is typically better than that produced with ordinary software and printers.

Similarly, a CAD file and one of several desktop manufacturing technologies can be used to create a 3-D model. Unlike the desktop published document, the resulting model will probably not be able to substitute for a finished object - at least not yet. However, the model produced in the process can be used as a prototype. In some cases, the prototype can be used to produce production casting molds, and as the materials and technology are refined, desktop manufacturing could become just that-a method of specialized production.

There are two large incentives for building a low-cost, high-speed, three-dimensional parts printer. One is to shorten product-development cycles.

Currently, producing prototypes is expensive and time consuming. For example, a set of molds for casting a metal part can cost anywhere from \$5,000 to \$50,000 and require a lead time of four to 12 weeks.

The other incentive for desk-top manufacturing is to enable the production of small batches of parts. Once again, the time and expense required to produce custom tools like molds and dies often make small batches uneconomical. Given such incentives, there have been many attempts worldwide to develop desktop manufacturing systems.

Like desktop publishing, desktop manufacturing saves both time and money when compared to traditional methods of creating 3-D models and prototypes. Conventional model-making methods, such as manual fabrication from clay, wood, or plastic or numerically controlled or electric charge machining, often take days, weeks or even months. These delays are one more roadblock in the race to bring a design to the final product stage, and ultimately, to market.

On the other hand, desktop manufacturing system can produce a model overnight, and in some cases, in matter of hours. As a result the entire design cycle is shortened considerably. And, desktop manufacturing can help lower the costs associated with product design. For example, a simple model created by conventional methods can cost anywhere from \$1,500 to \$ 25,000 or more, depending on its complexity and the modeling method used. In contrast a model created with desktop manufacturing can usually be created at fraction of the cost.

What's more, as a design is refined, modifications and revised models are often required. Simple mathematics indicates that each time a revised model is created with faster, less costly desktop manufacturing methods, the savings in time and money increase accordingly. A chain reaction of improved productivity and cost savings results, and in many cases, the quality of the final design has improved as well.

4.2 Rapid Prototyping Systems

Today, at least eight companies offer rapid prototyping systems. Conceptually, the market can be split roughly into two major approaches.

1) First is the photopolymer-solidification systems, which are in most widespread use today.

Photopolymer-based systems rely on a chemical process called photopolymerization, in which liquid resin converts to a solid polymer after exposure to ultraviolet (UV) radiation or visible light.

2) The second front is made of systems that use various materials deposition techniques to fabricate parts. These systems do not use liquid resins but employ thermo-plastics, polycarbonates, waxes, and paper which undergo a thermal reaction.

As competing methods proliferate, the industry is now searching for an umbrella term for the technology. Among the contenders are : rapid prototyping, free-form fabrication, desktop manufacturing, model making, and low volume manufacturing.

Rapid prototyping systems contain their own computers which receive the surface modeling data, orient it, and then cut it into thin, horizontal slices. The systems then build the physical prototype from the bottom up laying down material in the shape of these many thin sections. The building process may take anywhere from a few hours to few days depending on the speed of the mechanism, the thickness

of the layers, and the size of the part. All parts produced by rapid prototyping systems have a stratified or laminar appearance. Parts may have slightly roughened edges and the strength of the parts is greater in the plane of the cross sections than it is perpendicular to them.

Rapid prototyping systems employ a variety of materials and processes to build up the layers of the prototype models. Here is a description of each of them:

4.2.1 StereoLithography

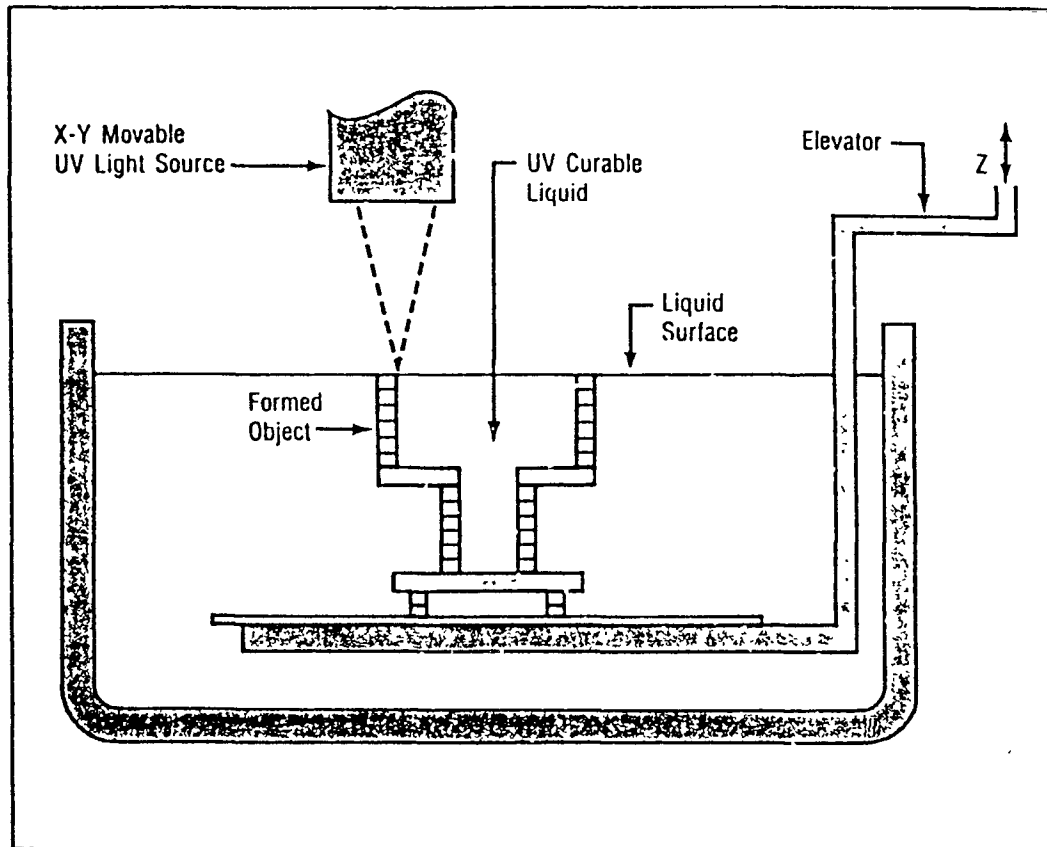
This process is the oldest and the most widely used of the rapid prototyping systems, and therefore it will be discussed in more detail as compared to other systems.

History

A small startup company called 3-D Systems (Sylmar, Calif.) has developed this process in mid 1987. Allowing companies to bypass tooling and produce in minutes or hours prototypes of computer designs.

Definition

Stereolithography is a three-dimensional printing process which produces copies of solid or surface models in plastic. The process uses a moving laser beam, directed by computer, to print or draw cross sections of the model onto the surface of photo-curable liquid plastic (figure 4.1).



The Basic diagram of how StereoLithography works

Figure 4.1

Using a stereoLithography Apparatus (SLA), solid or surface data is sliced by software into very thin cross sections. A Helium Cadmium (HeCd) laser then generates a small intense spot of ultraviolet (UV) light, which is moved across the top of a vat of liquid photopolymer by a computer-controlled optical scanning system. The laser changes the liquid photopolymer into a solid where it touches, precisely printing each cross section. A vertical elevator system lowers the newly formed layer, while a recoating and leveling system establishes the next layer's thickness. Successive cross sections, each of which adheres to the one below it, are built one on top of another to form the part from the bottom up. After the last layer is made, the part is removed from the SLA and flooded with high intensity ultraviolet light to complete the polymerization process. The part can then be finished by sanding, sand blasting, painting or dyeing.

Description

3-D Systems' most widely installed system, the SLA-250, includes either a 386 based slice computer with the Unix 386 operating system or a Unix-based Silicon Graphics Personal Iris workstation, in addition to a DOS-based personal computer with SLA control software, galvanometer mirror X-Y scanning system, laser, and an elevator mechanism housed in a vat of ultraviolet-sensitive liquid polymer.

Operating this equipment takes some skill. Forming a part require several steps as:

The first step is to create a 3-D solid model of a part in a CAD system and then design a structure that will link the part to the elevator platform and provide support during part fabrication, especially for designs with overhanging features.

Next the CAD model and support structure are converted to an .STL file format, using 3-D systems' interface specification. this format is offered by more than 33 CAD software companies, including Aries, CADKEY, IBM, Computer vision, Hewlett-Packard, Schroff Development, Control Automation, Intergraph, Parametric Technology, Prime, SDRC, Schlumberger, and Matra Datavision. Nearly all types of rapid prototyping systems accept or require using it.

The SLA slice computer divides the .STL file into cross sections that can range from 0.005 to 0.030 inches (0.13-0.76 mm) thick. It then stores the sliced data representing the model in .SLI files. Further processing allows the data to be read by the computer controlling the movement of the laser and elevator mechanism.

The galvanometer mirror X-Y scanner, driven by vectors of the cross sections, controls movement of the laser as it prints and solidifies the first cross section on the surface of the liquid polymer. The elevator containing the solid layer then lowers, and liquid covers it. A wiper blade passes across the liquid surface to speed leveling.

Successive printings of cross sections, each adhering to the preceding layer, create the part. Fabrication time depends on the specified layer thickness and part size. Thin slices create a smooth, accurate surface but require more compute time. For a small part, the system processes about one inch of thickness per hour. One hour of continuous processing will cure 4 cubic-inch of the polymer material.

After the part is processed in the SLA, ultrasonic cleaning removes excess material from crevices and openings. An alcohol bath then cleans off any unused polymer. Another method called wicking, can also be used, where blotting material soaks up any excess polymer.

Postcuring involves applying intense long-wave UV light to solidify the uncured liquid trapped in honey-comb-like part cavities (natural light curing also is possible). After about 30 minutes, the user can cut away the support structure from the part and sand-blast, hand-finish, or coat it to provide an appropriate surface finish.

The SLA-250 uses an acrylic polymer material that becomes hard but brittle after solidifying. This can be a limitation. The polymer, now costs about \$300-\$350 per gallon; however, material cost for a part fitting in a 6" (152 mm) cube averages less than \$25.

A less-brittle polymer is available for use in 3-D systems' larger SLA-500 prototyping system. This model's argon-ion laser provides more power than the helium-Cadmium laser used in the SLA-250. Laser speed is 100 ips (2540

mm/sec) versus 15 ips (381 mm/sec) with the smaller system, and the work envelope reaches up to 20 X 20 X 24" (508 X 508 X 610 mm). The SLA-250 is restricted to 10 X 10 X 10" (254 mm). The SLA-500 also uses 67 gallon (254 liter) of polymer, while the model 250 uses 7.8 gal (29 l).

A streamlined entry-level unit, the SLA-190, which doesn't have a wiper blade, provides about one-half the throughput speed of the model 250. Specifications include 7.5 X 7.5 X 9.8" (191 X 191 X 249 mm) maximum part size, 5.5-gal (21 l) vat capacity, and 0.010" (0.25 mm) minimum slice thickness.

An important thing about the liquid plastic used in stereolithography is that, it is not actually a polymer until it is cured. It starts out as a mixture of acrylic monomers (single molecules) and oligomers (short molecule chains that are not quite polymers). The mixture also contains a photoinitiator, a chemical which absorbs the energy from the 325-nm light and breaks down to form free radicals. These free radicals start the chain reaction of polymerization. The chain stops when oxygen in the resin absorbs the free radicals, so the polymerization only keeps going when the ultraviolet light is applied.

4.2.1.1 Photopolymers Used in SLA

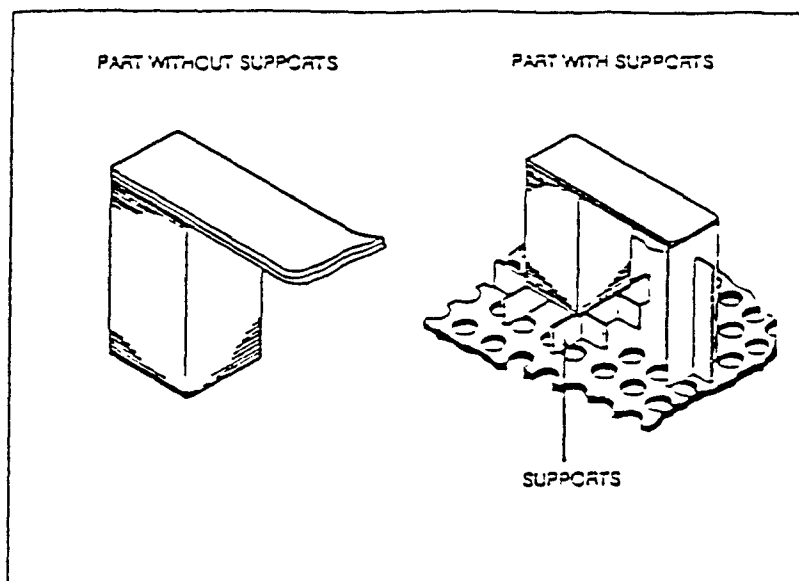
Presently, 3-D Systems recommends one specific plastic, Cibatool XB 5081. This polymer was developed by Ciba, a technical partner of 3-D Systems, for use with the SLA. The

rigid acrylic resin has been improved over the original resin that was used with the first SLA-1. It cures faster, and its cured strength is about 12 times as great as that of the previous polymer. It also has higher green strength. This is important because parts made with the SLA must generally be postcured. Finished parts contain some excess liquid which is drained by heating. Heat or ultraviolet light may also be used to complete the cure of the part (an ultraviolet oven is offered as an option to the SLA-250). The greater green strength of the new resin helps it resist distortion during this step.

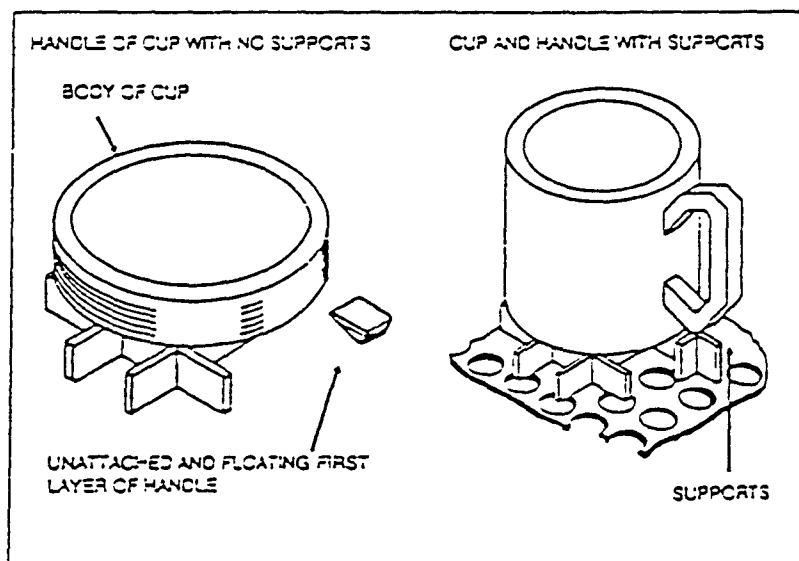
Potentially, a wide variety of polymers could be used for stereolithography. They could be soft and elastomeric, hard and brittle, or durable and tough. Most polymers could be modified to become photopolymers, though the photopolymer might not retain the properties of the original polymer.

The advantage of stereolithography is that, it is well proven, reasonably fast, and reasonably accurate. Service bureaus employing the systems say they can hold tolerances to $\pm .002$ inches per inch. The disadvantage of stereolithography is that the photosensitive polymers produce models which are translucent and quite brittle. Polymer manufacturers, such as Ciba Geigy and DeSoto Chemicals, are now bringing out resins which are tougher and stronger.

Stereolithography resins are foul smelling, so systems must be isolated in well-ventilated rooms. They must also be



Supports Prevent Deformation and Curl



Supports Anchor Unattached Layer Sections

Supports for Stereolithography process

Figure: 4.2

shielded from sunlight which will solidify the resin. Photosensitive polymers are expensive also. Parts whose cross sections contain islands of unsupported material require fixtures to support them as they are built. Otherwise these islands can curl or float out of position after they are formed (figure 4.2).

4.2.1.2 Coordinate System Used in SLA

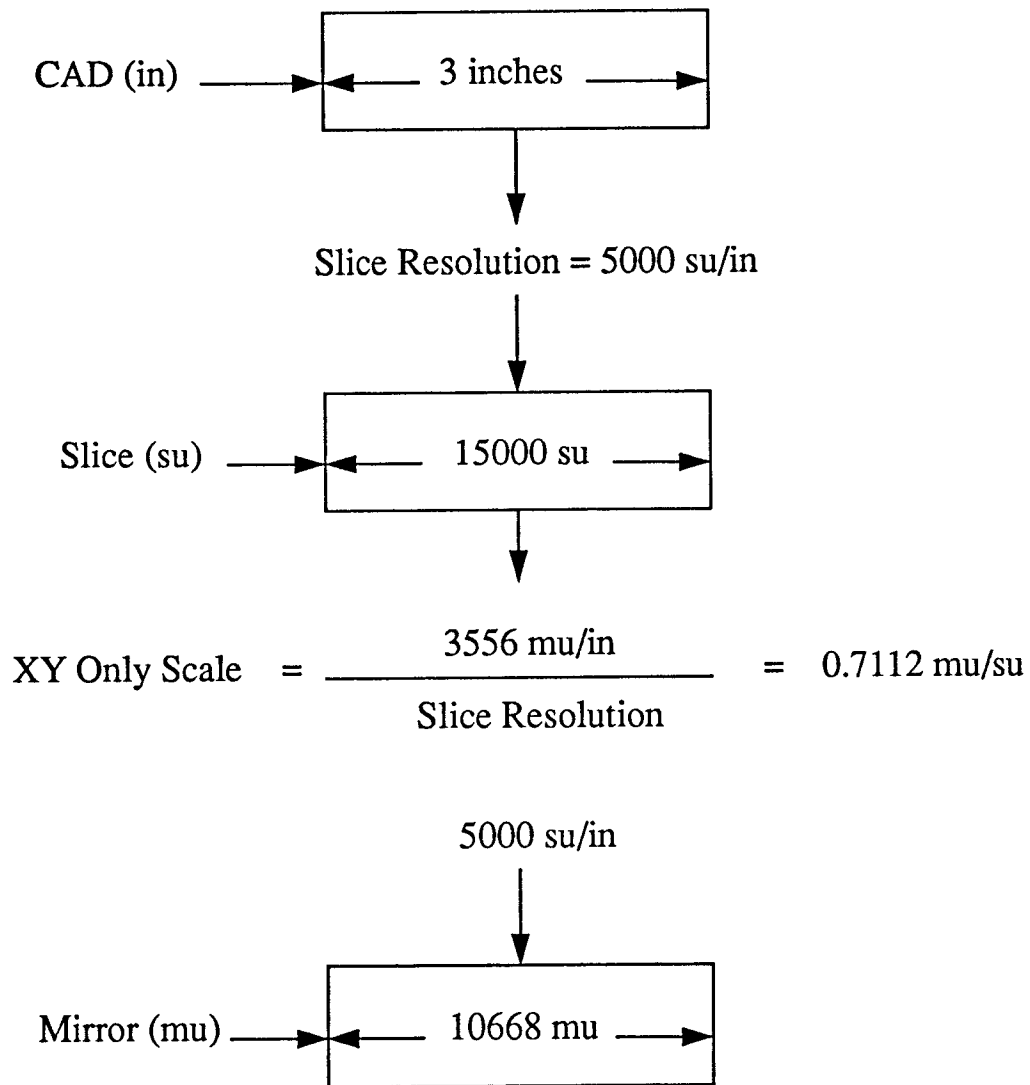
There are three coordinate systems which are used in building Stereolithographic parts. They are (listed in order of use): CAD system, slice system, and mirror system (figure 4.3).

i) CAD SYSTEM

CAD system coordinates are established within the CAD database, and are used to orient the CAD model in three dimensional space, relative to a global origin. The units within this CAD system are user determined, and can be either millimeters or inches.

ii) SLICE SYSTEM

The slice system defines a three dimensional space that facilitates the cross sectioning and vertical slicing of the model. A three dimensional grid of slice units is superimposed on the CAD space with common origins. The user defines the size of the slice unit which can range from 1000 to 10000 to the inch (40 to 400 to the millimeter).



Coordinate Systems

Figure: 4.3

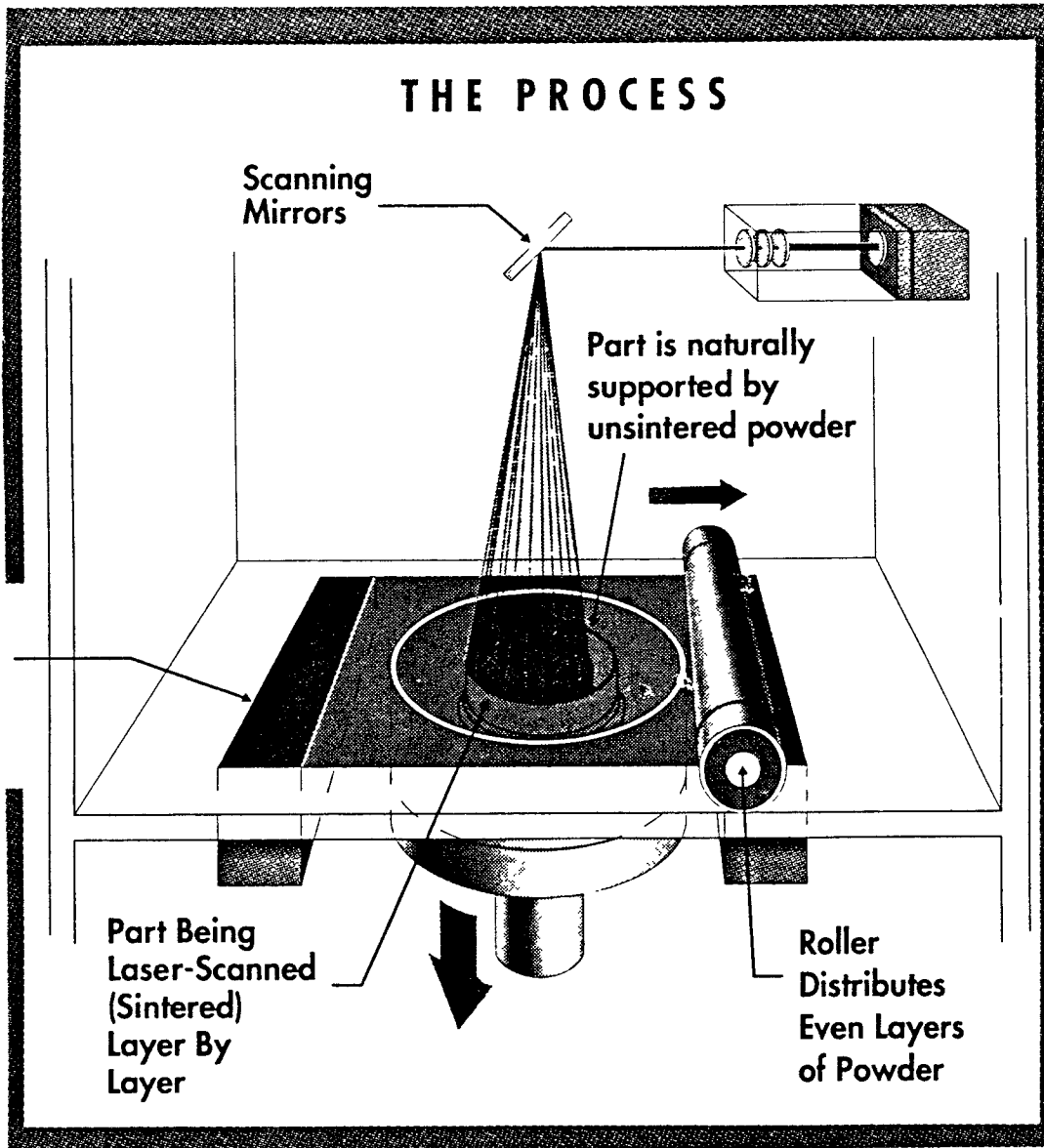
iii) MIRROR SYSTEM

Mirror space is a two dimensional plane located at the surface of the liquid plastic. This system is used to internally position and move the laser beam by rotating a set of mirrors. The smallest distance within this coordinate system, known as mirror unit, is 0.0002812 inches (0.0071428 millimeters). Mirror space is normally transparent to the user.

4.2.2 Selective Laser Sintering

As its name implies, selective laser sintering employs a high energy laser to fuse or sinter powder into a solid object. Because it is a sintering process, it also holds the potential to work with metals. Like the stereolithography system, the SLS laser traces the shape of each cross section, fusing powder in the thin layer. A mechanical roller then spreads more powder across the top of the finished part and the laser traces the next cross section.

Sintering fuses powders into a solid mass by means of externally applied energy (figure 4.4). Heating the particles does not melt them completely, but rather lowers their viscosity to overcome their surface tension. Selective laser sintering is similar to the process of powder metallurgy. However, powder metallurgy first forms parts by compressing the powder in a die, then sintering it in an oven. Selective laser sintering does not require the use of a die, but it is not yet commonly used with metals.



Selective Laser Sintering process

Figure 4.4

4.2.2.1 Materials Used in SLS

Selective laser sintering systems can work with three materials: wax (for investment castings), polycarbonate, and polyvinyl chloride. In the near future, ABS, Nylon, and some ceramic materials may be added to the list. Research is being done to employ SLS in metals.

The advantage of SLS over stereolithography is that it employs a wider variety of materials with better mechanical properties than photopolymers. These materials are also cheaper than photopolymers. Furthermore, because SLS employs powder, rather than a tank of liquid, no special fixtures are needed to support parts with islands in their cross sections. The disadvantage of selective laser sintering is that tolerances may not be held as tightly as with stereolithography. Plus or minus five mils per inch is normal for these systems. Because the process is newer, there are fewer SLS in use and manufacturers have less experience with them. The surface finish of PVC parts is quite smooth, although other materials exhibit a laminated appearance.

The details of parts made with selective laser sintering is determined partly by the laser, as in photochemical methods. The SLS system laser has a spot size of about 0.020 in., a minimum step size of 0.0003 in. and repeatability of +/- 0.005 in. However, detail also is determined by the powder size.

4.2.3 Fused Deposition Modeling

Fused Deposition Modeling (FDM) is a rapid prototyping technology which safely and quickly generates accurate physical models. In this process a conceptual geometric model is created on the CAD workstation. It is then imported into a UNIX-based workstation where it is sliced into horizontal layers that are down-loaded to the 3-D MODELER. Semi-liquid thermoplastic material is extruded and then deposited into ultra thin layers from the lightweight FDM head one layer at a time. This builds the model upward off a fixtureless base (figure 4.5).

A spool of .050 inch diameter modeling filament feeds the FDM head. Model materials can be changed over in a few minutes.

Maintaining the semi-liquid modeling material just above the solidification point is fundamental to the FDM process. The thermoplastic melt temperature is controlled to 1 degree Fahrenheit above solidification. The material then solidifies as it is directed into place with an X-Y controlled extruding head nozzle that creates a precision laminate.

Successive laminations, within the .001 to .030 inch thickness range and a wall thickness of 0.009 to .250 inch range, adhere to one another through thermal fusion to form the model. Stratasys maintains an overall tolerance of +/- 0.005 inches in the X, Y, Z axis over the entire 12 inch cubed working envelope.

Fused Deposition Modeling (FDM)

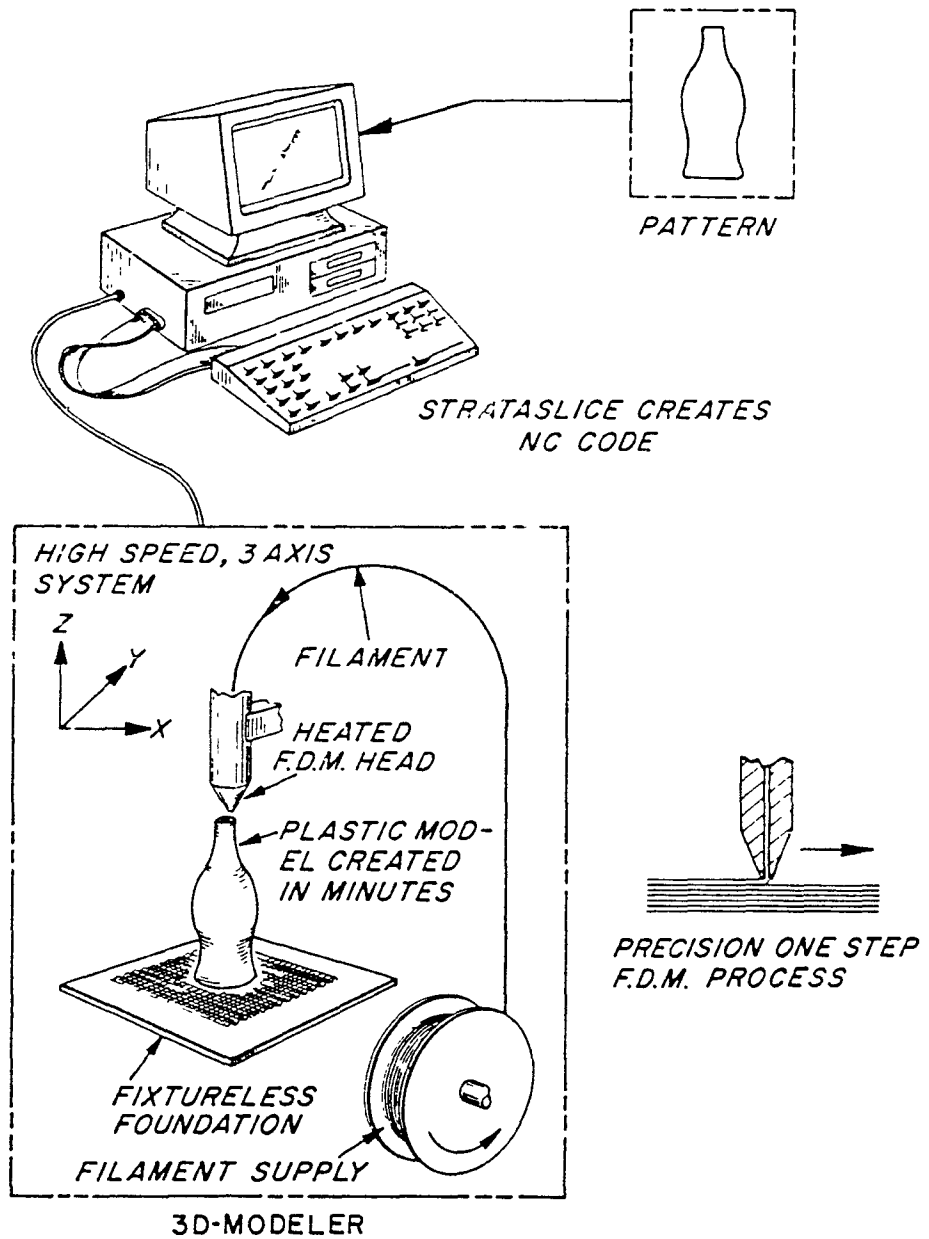


Figure: 4.5

Repeatability measures how closely the machine can run the same tool part 100 times, with the tool part remaining within tolerance and resolution. The Stratasys 3-D MODELER holds repeatability to +/- 0.001.

Speed is an important benefit of this technology; many models can be produced in minutes rather than hours or days. As no curing is required, the FDM technique enables the designer to create multiple versions of a part design within a short time frame in a user friendly manner.

The process operates at moderate temperatures in the range of 180 to 220 degrees Fahrenheit, making it safe for office use. By comparison, the temperature is similar to that of a hot cup of coffee. There is no worry of possible exposure to toxic chemicals, lasers or liquid polymer baths. In this process no powder is used and there is no messy cleanup. Concern over disposal of hazardous materials is also eliminated.

This 3-D MODELER has the ability to create a support in mid-air rather than building the support up from the base in some applications. the system is also capable of extruding plastic into free space depending on the part geometry. When supports are not needed, the FDM head forms a precision horizontal support in mid-air as it solidifies.

4.2.3.1 Materials Used in FDM

The FDM technology allows the use of a variety of modeling materials and colors, with new materials continually under

development. All are inert, non-toxic materials developed from the range of commercially available thermoplastics and waxes. The ability to use different materials allows the user to match the material to the end use application of the prototype, whether that is a pattern for tooling or as a concept model.

Currently, there are three materials: a machinable wax, a tough plastic polymer and an investment casting wax. These thermoplastics and waxes soften and liquify when heat is applied.

The investment casting wax is an industry standard investment casting material. This wax rapidly dewaxes from the shell using normal investment casting procedures and provides superior surface finishes. Because this is a standard investment casting wax, it can become part of the foundry's normal recycling process.

The machinable wax, a wax-filled plastic adhesive material, is primarily used for conceptual modeling and spray metal modeling. For instance, the accuracy of the model allows its use in the spray metal molding process for injection prototyping. Both the investment casting wax and the machinable wax can streamline the user to go directly to soft tooling using the model as the spray metal injection molding processes.

The plastic filament is a tougher material producing sturdier models suitable for concept models or form, fit and

some function applications. It is strong yet flexible with good surface finish.

Fused Deposition Modeling uses a spool based filament system to feed the material into the modeler. The spool based system has proven to be a significant strength of the 3-D MODELER.

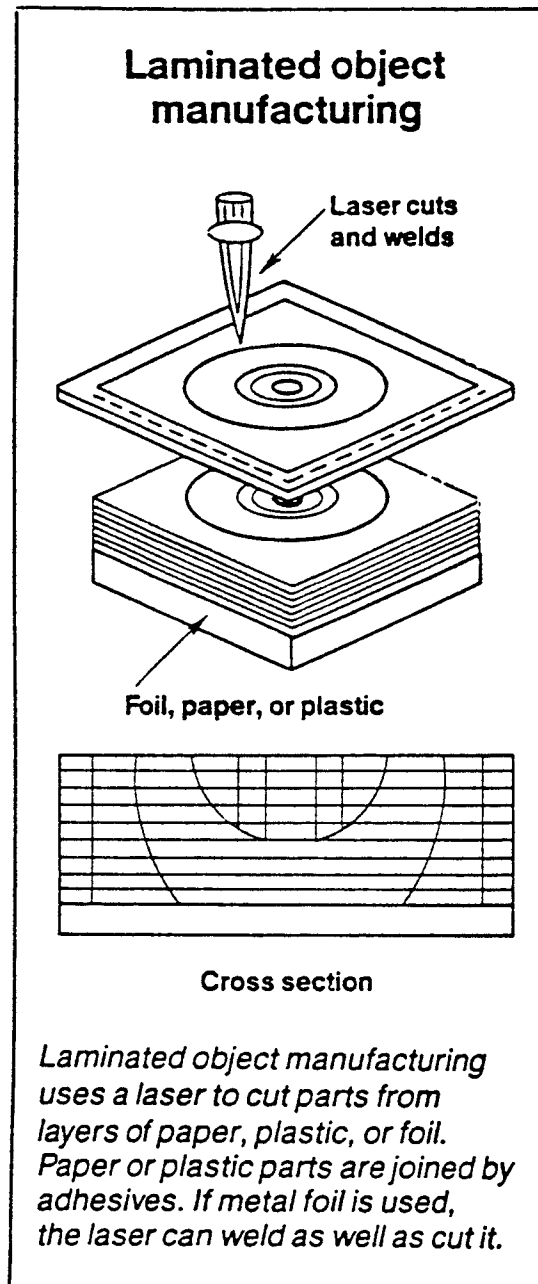
The spools give the user the ability to change material in about one minute by threading the desired material into the prototyping unit. The previous material is purged out of the orifice in about 5 minutes. There is virtually no waste and no vat to clean out; you only use what is required for the model.

4.2.3.2 Material Consumption

The material to produce a part are cost effective, usually under twenty dollars per part. For example the material for one golf club head in the machinable wax costs approximately \$ 9.00 and one half-mile spool of material can produce roughly 20 club heads.

4.2.4 Laminated Object Manufacturing

Laminated object manufacturing (LOM) is another method for building up parts layer by layer using lasers. But in a way, it is the opposite of the other methods. Rather than building up a part by adding material to a stack through a forming process, layers of a sheet material are attached to a stack, and the unused portions are cut away by the laser



Laminated Object Manufacturing Process

Figure: 4.6

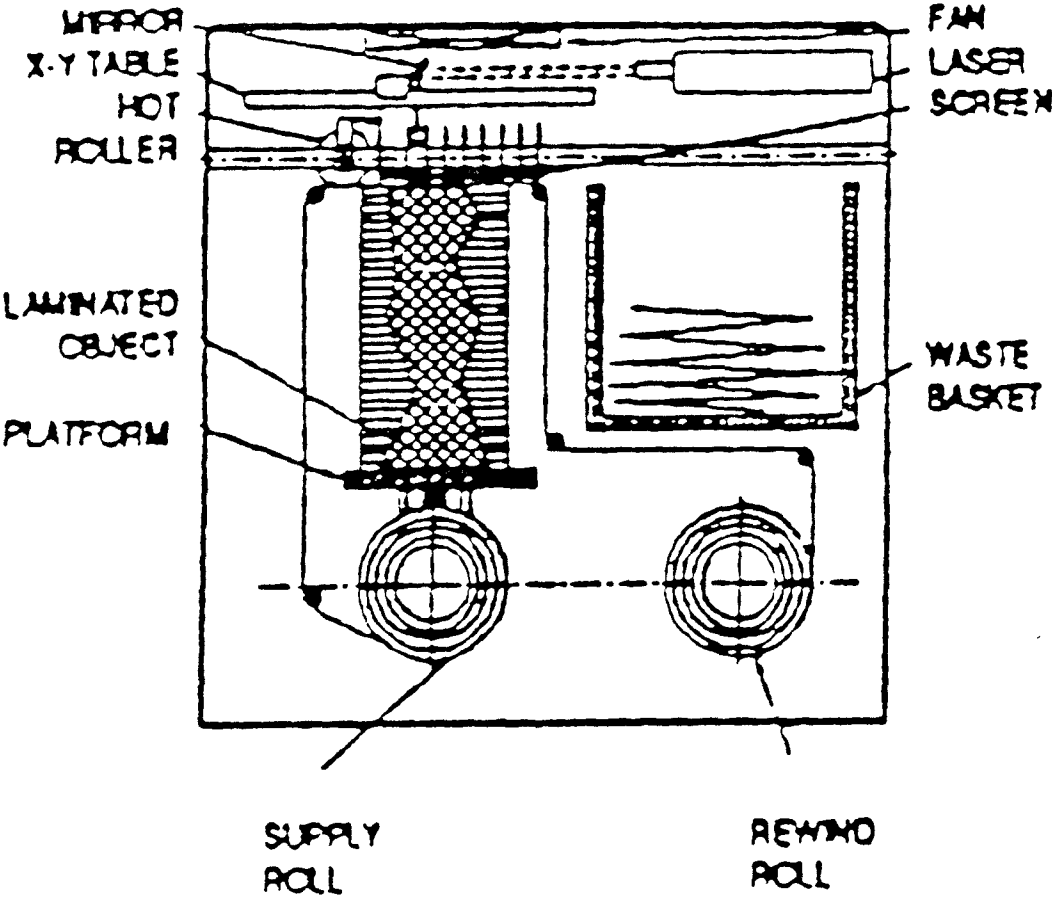
(figure 4.6). However, the laser can also be used to join the layers.

Many film, foil, and sheet materials can be used. A layer is first glued to the stack then cut with the laser beam. Laser power is adjusted to cut through only one layer of the lamination. Cutting is done around the periphery of the lamination, and because a solid is being cut, rather than formed, it takes no longer to create a thick-walled part than a thin-walled one (figure 4.7). A company claims that this process is faster than other forming processes such as stereolithography or Laser sintering.

The advantage of this method is that over others is that, sheets may be used as thin as .001 to .005 in., enabling surface definition as fine or finer than competing methods. The process also, does not produce internal stresses which may cause warping.

The materials used are also less expensive than the photopolymers required for stereolithography or photochemical machining. Paper works especially well. In fact, paper models made this way may eventually be used for investment casting. Other materials that can be used include metallic foil coated with a metal with a lower melting temperature, plastic films covered with an adhesive, or composite materials such as fiberglass or graphite sheets.

This system also uses .STL files. Despite the fact that the laser is cutting instead of building material, the same



View of the LOM process

Figure: 4.7

file can be used because it contains the surface information, which remains the same. Then the laser cuts the part by layers. It can also make additional cuts, called parting lines, or perforations that make it easier for users to remove the excess material.

When material is cut out of the object it can be either removed at once by automated vacuuming after forming each layer, or left in to support higher layers of material. If the material is left in, it can be separated from the finished part more easily, just as a mold is separated from the molded object.

When metal foil is used the finished part is furnace brazed together. It is also possible to use the laser itself to braze the cross sections together. The completed part can be finished conventionally. An automated surface grinding system may eventually be incorporated into the LOM system.

4.2.5 Light Sculpting Process

This process is some what similar to other photopolymerizing process it is some what faster than others because it solidifies liquid photopolymers a layer at a time rather than a point at a time as other laser based systems do.

In the LSI-0609MA system, a 140-watt ultraviolet lamp irradiates an entire layer of liquid acrylate photopolymer through a photomask. In a process akin to printed circuit board fabrication, the mask, which is a negative image of a slice or cross section, is produced by using a photoplotter

to transfer the inverse image from a solid or surface CAD model to the glass masking plate. Transparent and opaque patterns on the photomask correspond to the solid and hollow portions in the slice through the object.

To prevent warpage and shrinkage distortion, the irradiated surface is constrained and supported from above by a rigid glass plate positioned below the mask.

Each layer is formed in seconds. A new coat of polymer is then applied and the next masking plate is positioned above the workpiece ready for ultraviolet irradiation. The total cycle time for each layer is less than one minute.

In future LSI systems Inc. will not be using the photoplotter masks. Negative slice images will be transmitted directly to the polymer surface using a flat array of backlighted liquid crystals under individual control.

4.2.6 Ballistic Particle Manufacturing Process

This process known as BPM process, is developed by Perception Systems Inc., It involves using a computer-controlled, independently targeted jet of thermoplastic ink particles to construct parts. Particles are fired from an ink jet mechanism to a platform where they hit and solidify. The mechanism is positioned by a three-axis robot. A part is produced by printing multiple cross sections with cold welding or rapid solidification providing cohesion between particles. Tolerances are controlled by particle size and

location. Shrinkage and warpage are said to pose no problems.

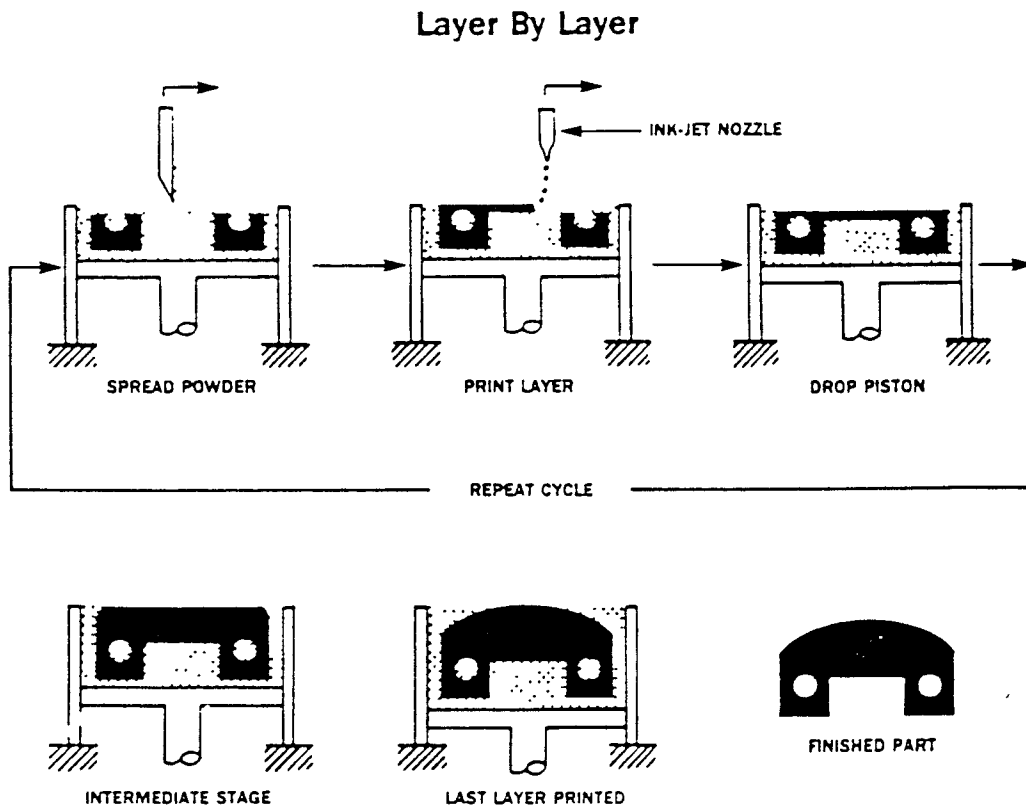
According to the Perception Systems, the BPM process is not limited by part size or materials: almost any meltable material can be used, as can multiple materials. And because BPM is a constant build process, it does not hesitate between layers, and therefore produces parts relatively quickly.

4.2.7 Free Form Fabrication

A team of researchers at the Massachusetts Institute of Technology (Cambridge) is developing a free form fabrication technology called three-dimensional printing (figure 4.8), with the goal of direct production of tooling and functional prototypes from CAD models. The research project is funded by many big companies.

MIT's three-dimensional printing system uses a continuous-jet inkjet printing head to selectively deposit binders on layers of powders. The result is a solid object composed of sequentially printed two dimensional layers. This process is much cheaper than any other process available in the market.

Ceramic powders are used to produce ceramic cores and shells for metal casting and on porous ceramic preforms for metal-ceramic composites produced by infiltrating pressurized molten metal. So far small parts of alumina have



Three-dimensional printing sequence used for rapid prototyping.

Figure: 4.8

been produced with colloidal silica as the binder. Researchers are planning to make parts of silica, zirconia, and silicon carbide soon, and have also started investigating metal powders such as steel, stainless steel, and nickel-based superalloys.

In three dimensional printing, each layer begins with a thin distribution of powder spread over a powder bed by a cylindrical rod, an arrangement similar to that of DTM's SLS system. From a CAD model of the desired part, a slicing algorithm creates the cross-sectional layers to be built. An inkjet printing head primed with binder material is raster-scanned over the powder bed by a stepper motor-driven x, y positioning device that is controlled by an 80386-based computer. The binder is distributed in very small droplets by means of continuous-jet printing heads. When they impact, the binder droplets join powder particles to form a solid.

After scanning, the piston that supports the powder bed and the part in progress lowers so that the next powder layer joined. This layer-by-layer process repeats until the part is completed. Following a heat treatment, the loose powder is removed, leaving the fabricated part. The current machine's build volume is about 3 cubic inches.

The team's eventual goal is a scaled-up version with a 100-nozzle print head that is capable of building parts up to 12 x12x24 inches.

4.2.8 Brute-Force Imaging

As an early entrant into the rapid Prototyping field, du Pont/Somos Venture was expected to make its weight felt in no uncertain terms. The company was formed by du Pont Imaging Systems (New Castle), When it unveiled the Somos 1000 it was suggested that the unit was one of the more sophisticated model-building systems yet produced. Unfortunately, to date du Pont's foray into rapid prototyping has remained mostly on hold because of the company's reluctance to sell equipment and because the photopolymer market remains relatively small.

The philosophy in developing the System 1000 was the brute-force method of solid imaging. The Somos 1000 operates in a manner similar to 3D systems' SLA machines, it uses a 500 milliwatt argon-ion ultraviolet laser with a high-precision scanning system and a high-speed beam modulation. Quoted accuracies for the System 1000 are:

x-axis 0.002 inch/inch.

y-axis 0.002 inch/inch.

z-axis 0.006 inch/inch.

The Somos 1000 uses a unix work station to process CAD data and a windows-based user interface with extensive graphics capability. The system accepts .STL files.

Models are built in a one-cubic-foot vat that is equipped with a high speed resin coating system to lay down new layers of liquid photopolymer. Its laser beam has a sufficient power to fully cure the Somos 2100 photopolymer

as each layer is formed. For increased strength, a post process heat treatment causes additional polymer cross linkage.

The Somos 2100 photopolymer is substantially different from other photopolymers because acrylates make up only a minor part of its composition. It is claimed by the company that the 2100 formulation has a high photospeed, low shrinkage and warpage, wide exposure latitude, flexible and homogeneous photoformed parts, and good layer-to-layer adhesion.

The research is being done on a variety of photocurable materials for different applications, some flexible, some rigid, some transparent, others suitable for investment casting use.

A comparative chart of the specifications of each process is provided in table 4.1

Proliferation of rapid prototyping technologies gives a range of options

Company	Process tradename	Material	Part size capability, in.	Equipment cost, \$	Light source
3D Systems	StereoLithography (SLA-250)	Photopolymer	10 x 10 x 10	185,000	Helium-cadmium laser
3D Systems	StereoLithography (SLA-500)	Photopolymer	20 x 20 x 24	385,000	Argon-ion UV laser
3D Systems	StereoLithography (SLA-190)	Photopolymer	7.5 x 7.5 x 9	95,000	Helium-cadmium laser
Du Pont	Somos	Photopolymer	12 x 12 x 12	350,000	UV laser
Laser Fare ^a	Optical fabrication	Photopolymer	12 x 12 x 12	— ^b	Argon-ion visible light laser
Quadrax	Mark 1000	Photopolymer	12 x 12 x 12	230,000	Argon-ion visible light laser
Cubital	Solider	Photopolymer	20 x 14 x 20	490,000 ^c	UV lamps
Hydronetics	Laminated object manufacturing	Sheet ^d	11.5 x 11.5 x 17	75,000 ^e	CO ₂ laser
DTM	Selective laser sintering	Powders ^f	12 x 15	— ^g	CO ₂ laser
Light Sculpting	Light sculpting	Photopolymer	6 x 6 x 6	75,000 ^e	UV lamps
Perception Systems	Ballistic particle manufacturing	Thermoplastic ink	12 x 12 x 12	50,000–80,000	None needed
Strata Sys	Fused deposition modeling	Thermoplastic filament	12 x 12 x 12	178,000 ^h	None needed

^a Operates as a service bureau. ^b Part costs have ranged from \$500 to \$12,000. ^c Turnkey system; price includes all components. ^d Includes plastics, metals, paper.
^e Beta site price—commercialized unit will cost \$100,000. ^f Includes engineering plastics, ceramics, metals. ^g \$15,000/month to rent.

TABLE NO: 4.1

CHAPTER 5

DESIGN AND MANUFACTURE OF THE 3-D MODEL

5.1 INTRODUCTION

The primary target of this thesis is the application of a desktop manufacturing technique to build complex parts, and the evaluation and explanation of the procedures involved in building the part from concept to prototype. DTM is a technique which is constantly changing the way of thinking of engineers in the design, test and fabrication of complex parts.

For this thesis an actual impeller of a centrifugal pump was selected because of its complex shape. In practice to develop such shape is quite cumbersome and require ample labor and technique.

As far as the profile of the blade is concerned, due to the varying thickness, its design on CAD and transfer to the SLA machine, was itself a complicated effort, and require.

5.2 Facilities Available at NJIT

The facilities and services available at NJIT are used to perform the experiments in this thesis, are explained briefly as follows:

1. COMPUTER SYSTEM
2. IDEAS-PACKAGE
3. SLA-250

5.2.1 Computer System

5.2.1.1 Sun Workstation

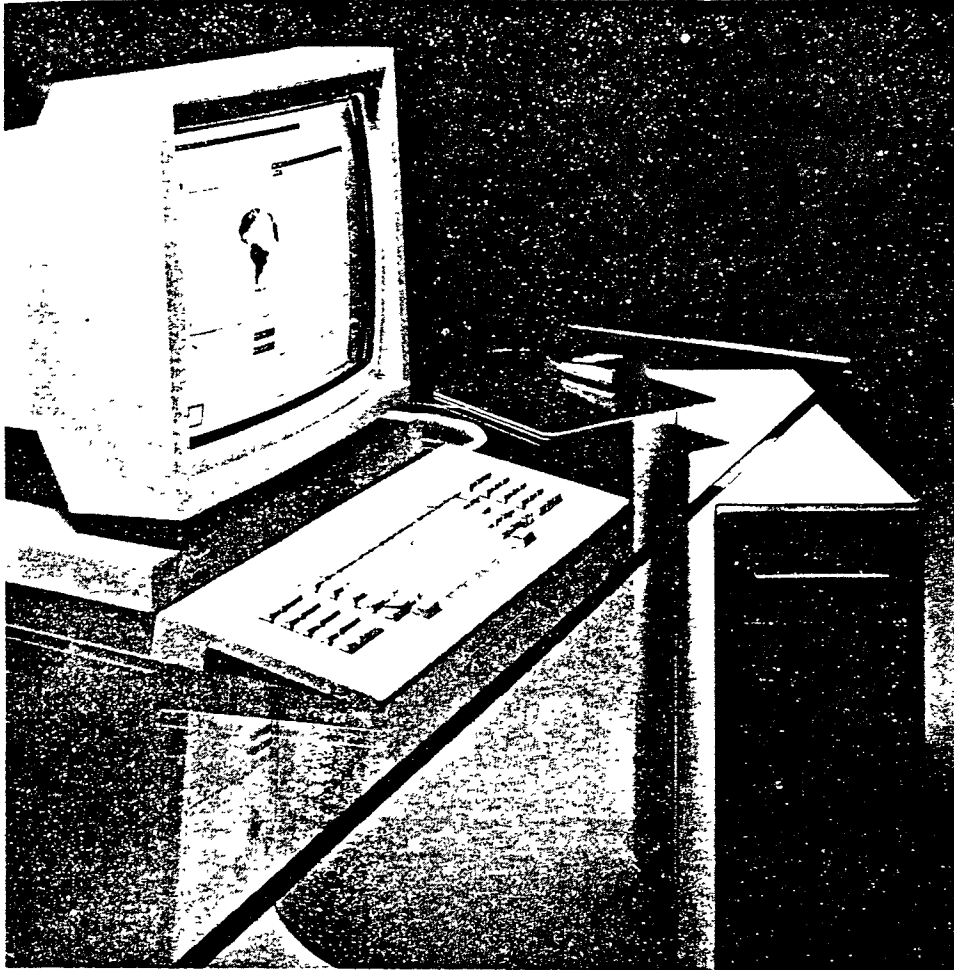
In NJIT two labs are equipped with the SUN system. The MSAOL has 7 Sun Sparcstation 1+ color workstations (figure 5.1), and many others, each workstation has 16MB RAM and 208 MB (90MB swap, 55 MB scratch) disk. The color monitors are 19", have 1152 x 900 pixels, and can display 256 colors at once. They also have accelerated 2D graphics.

The operating system for all workstations is SunOS 4.1.1, a UNIX variant. UNIX can support multiple users, as well as multiple tasks, so users can remotely login to workstations from other workstations or terminals.

All workstations and X terminals are networked to each other using the TCP/IP and Ethernet communications protocols. The network medium is thin coax cable. In addition, the labs are connected to the NJIT campus network backbone, which is in turn connected to off-campus networks, including the internet.

5.2.1.2 Tektronix 4693DX Color Imager

The Tektronix 4693DX produces 8.5 x 11 inch color prints on opaque paper or transparencies. The 4693D is capable of 256 colors out of a choice of 16.7 million, or 256 gray levels. The resolution is 300 dots/inch. It is connected in such



Interactive Sun Microsystems, CAD workstation

Figure: 5.1

away that from any Sun workstation it could be accessed easily.

5.2.2 I-DEAS Package

I-DEAS (Integrated Design Engineering Analysis Software) is an integrated package of mechanical engineering software tools. It is available at most of the Sun workstations at NJIT. The purpose of this software is to facilitate a concurrent engineering approach to mechanical engineering product design and analysis. This software allows different groups in a company to share design geometry and exchange information freely for a variety of applications. In our case our target is the SLA model therefore we are limiting our efforts to a single feature of this package.

5.2.2.1 I-DEAS Basic Structure

I-DEAS is made up from a number of "families" of software modules, each subdivided further into "Tasks", all executed from a common menu and sharing a common database. The main families are :

1. Solid modeling
2. Drafting
3. Finite Element Modeling
& Analysis
4. System Dynamics
5. Test Data analysis
6. Manufacturing

As we are only concerned with solid modeling, a brief description looks necessary before proceeding further in the experiment.

5.2.2.2 I-DEAS Solid Modeling

Solid modeling is more than just a way to make three dimensional computer pictures of parts and assemblies. Even if making visual images of design concepts was the only use for solid modeling it would be a useful tool, but the advantages go well beyond that. The real advantages of the solid model are all of the other "downstream" uses of this three dimensional model. The solid model is the starting point and a shared information source containing the geometric definition of the parts and assemblies in an MCAE design project. The geometry taken from the solid model can be used for making prototypes on a SLA, interface studies, mass properties calculation, kinematic analysis, stress analysis, dynamics, manufacturing, testing, or other applications, only the first option is used in this analysis.

This family of I-DEAS contains several tasks for part modeling, assembly modeling, and mechanism analysis. there are many different ways these tools may be used together as a design evolves.

5.2.3 StereoLithography Apparatus (SLA-250)

This is the basic machine which is used for the experiment in this thesis. The SLA stands for StereoLithography Apparatus, it is built on the basic C-frame design used by most machine tools. A base holds a 7.8 gallon (29.5 liter) polymer vat. An elevator table, upon which the models are developed, is located in the vat. On the top of the basic machine column is a 12.5 milliwatt HeCd (helium cadmium) laser that generates an ultraviolet (UV) beam. Servo motors, receiving their commands from the machine control unit, drive the set of mirrors that reflect the laser beam to the surface of the polymer in the controlled path that will create each slice of the model.

It is important to note that the laser power level is very low - only a fraction of one watt. By comparison, lasers that are used to cut steel sheet range from 500 to 1500 watts. However, normal precautions that surround the use of any laser have been observed.

The machine control unit is very similar to a computer numerical control on a machine tool. It moves the laser beam over the surface of the Polymer in the vat. The only movement in the vat, itself, is the slight drop of the elevator platform after each layer, or slice, has been solidified. This is followed by a platform raise, a sweep to level the polymer, and a drop. When the program has been completed, the platform lifts the finished model above the liquid surface.

A second system unit available in NJIT is the PCA-1 (Post Curing Apparatus), a chamber in which is generated an intense long wave UV light that provides the final cure for the part created by the laser. The curing time varies according to the part geometry, part size, and type of polymer resin. In this thesis it varied for frontshroud, backshroud and the complete impeller.

A third, and necessary, component used in this procedure was the "slice" computer, an integral part of the SLA-250, it took the part design file from the CAD system (I-DEAS) and literally sliced it into layers. They become program steps directing the laser beam to cure the polymer. By building one layer on top of another creates the model.

5.3 Steps Involved in Building the Part

The StereoLithography process adopted for building the centrifugal impeller is composed of ten major steps as shown in figure 5.2.

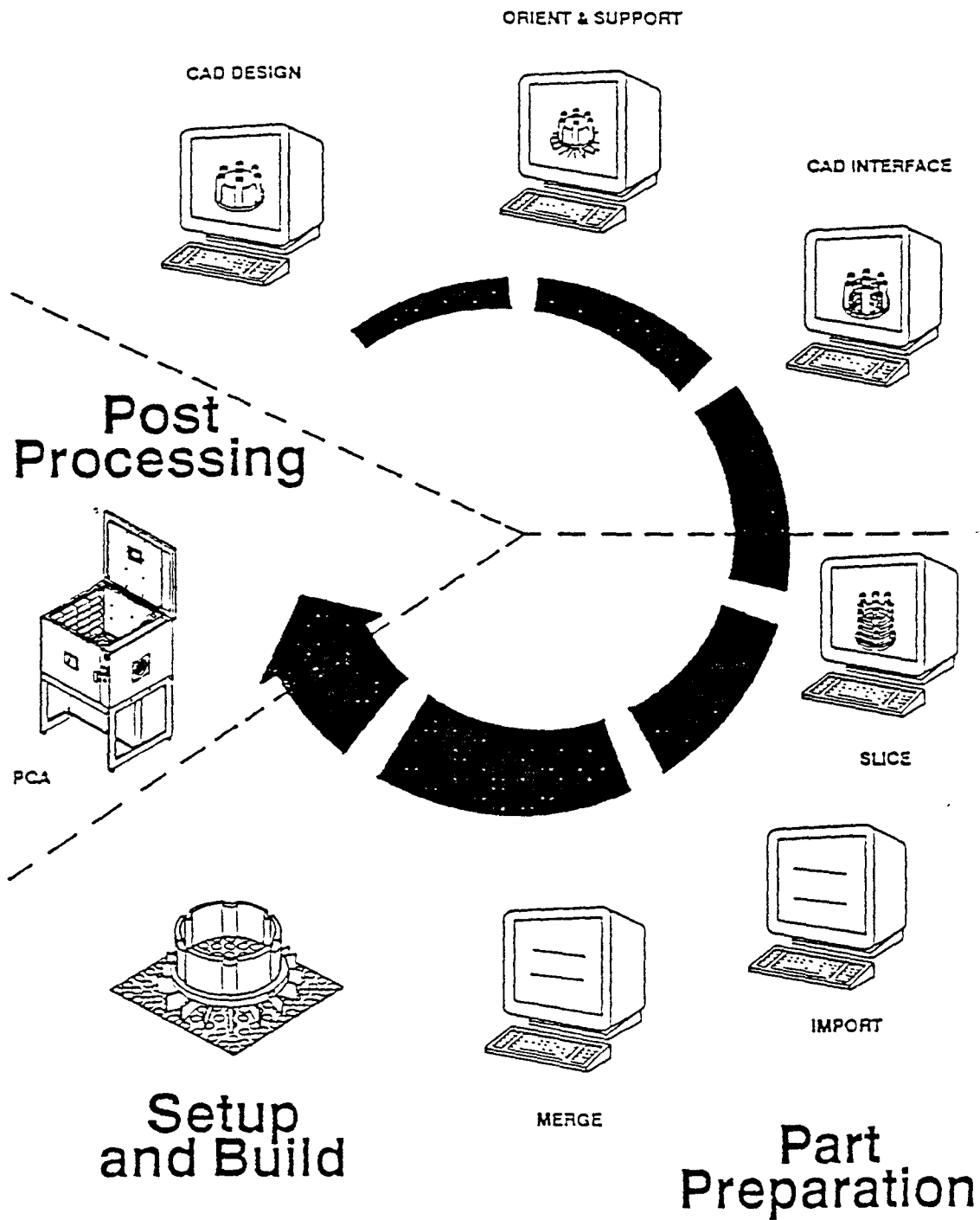
5.3.1 CAD System Stage

A CAD system (I-DEAS) was used for building the part, the first three steps construct the object data for use on the SLA, are as under:.

Step 1 - CAD Design

This step comprise of all the procedures involved in making a solid model through the I-DEAS package. There fore this

CAD Process



The StereoLithography Process

Figure: 5.2

step is further divided into eight steps which explains completely how the parts were build. The centrifugal impeller selected for the experiments was divided into three components facilitating the structure building, therefore all of the following steps will be based on them:

- a) Front Shroud
- b) Blades
- c) Backshroud

i) Making wireframe

Wireframe geometry is a collection of points and curves (lines, arcs, circles and splines) in three dimensional space. Before building the part wireframe geometry was used at the beginning of the design to allot space for different parts in the assembly. This geometry was then used as an aid in creating the final part geometry to fit where it belongs in this 3-D layout.

ii) Making Profile and Skin groups

Profiles are two dimensional points and curves connected end-to-end to define 2-D outlines. A skin group is a collection of profiles representing cross sections through a part, or collection of wireframe curves defining a surface. The complex geometry of the blade was created by first making a wireframe to create a 3-D layout (figure 5.3), then 12 profiles were created at different cross-sections of the

blade using the R, Z and theta coordinates (see appendix for data). Each profile was then stored.

To create a skin group from the profiles, stored orientation method was used, since it is a very convenient method for creating a skin group if the profiles were stored in proper orientation, which was taken care while storing the profiles (figure 5.4).

The profiles of the front and back shrouds were also created (figure 5.7 and figure 5.8) with the help of their respective wire frames, and then stored.

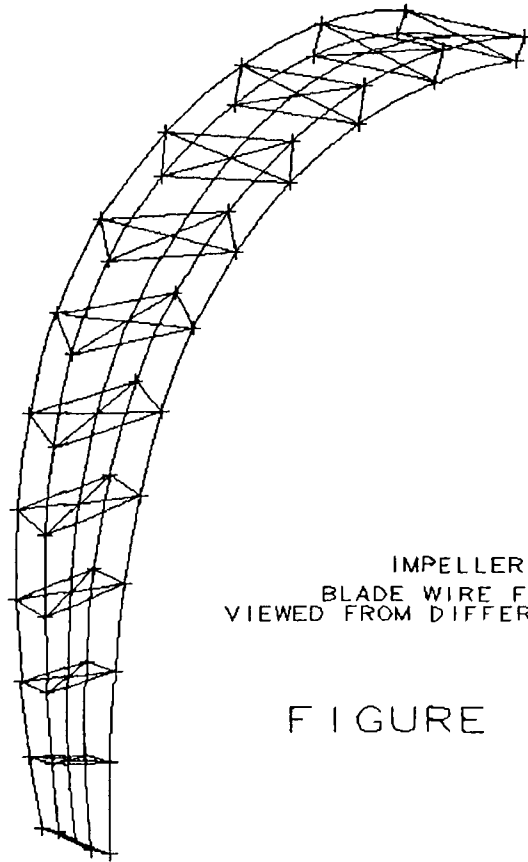
iii) Creating object from Skin group and profiles

All of the above mentioned steps were accomplished through the "construction geometry", task of the I-DEAS package, but to create a solid model from a profile or skin group another task named as "Object Modeling" is to be used.

Objects can be created from one profile by extruding or revolving , or they can be created from a series of profiles by skinning.

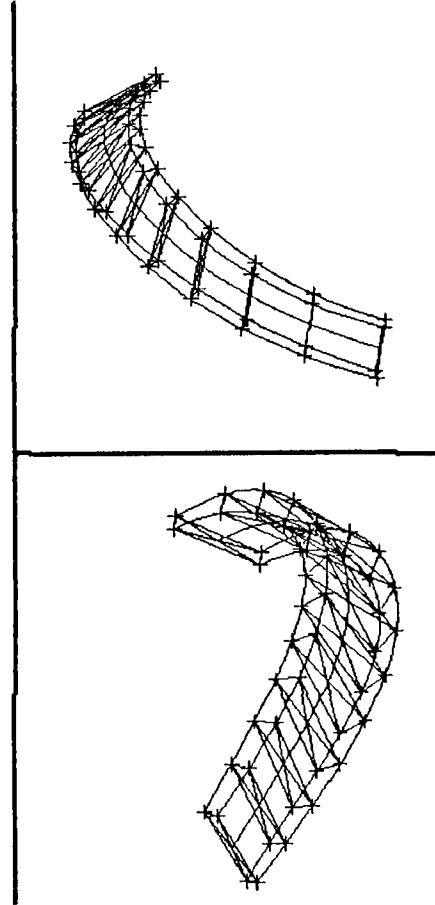
The front and the back shrouds were created by revolving their respective profiles along the local Y-axis of the work plane, and stored (figure 5.10 and figure 5.11).

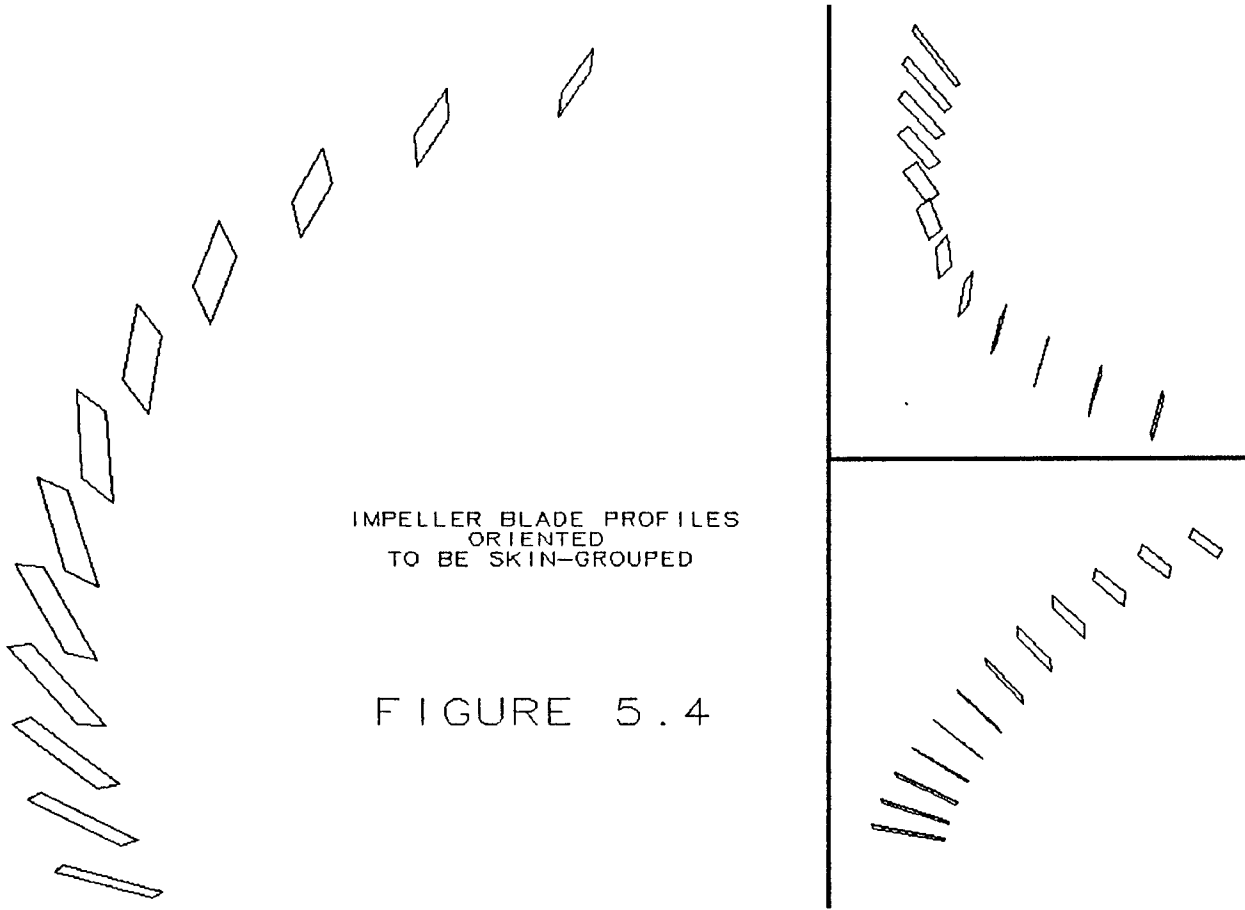
The body of the blade was created by skinning the skin group stored, having profiles in the desired orientation (figure 5.5). The blade formed represents a solid model and is stored as a solid object in object modeling task (figure 5.6 and figure 5.9).



IMPELLER
BLADE WIRE FRAME
VIEWED FROM DIFFERENT ANGLES

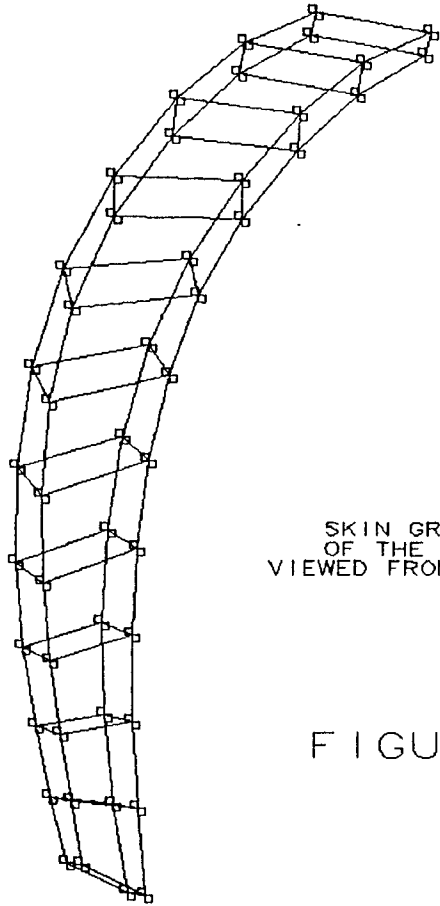
FIGURE 5.3





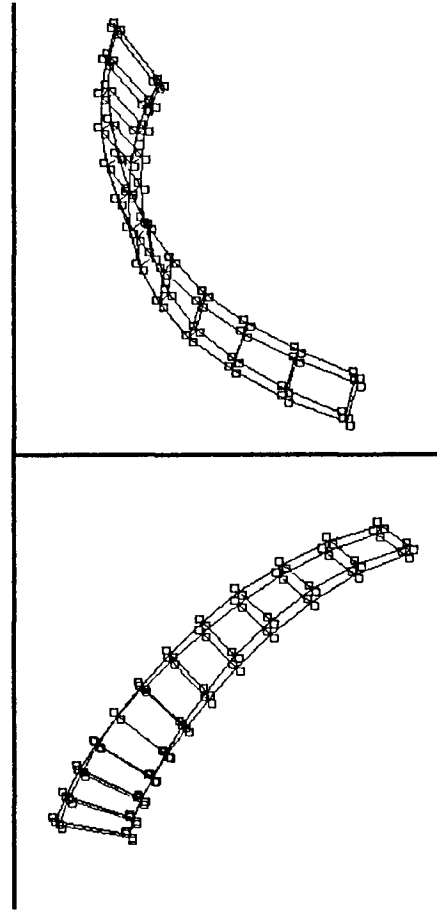
IMPELLER BLADE PROFILES
ORIENTED
TO BE SKIN-GROUPED

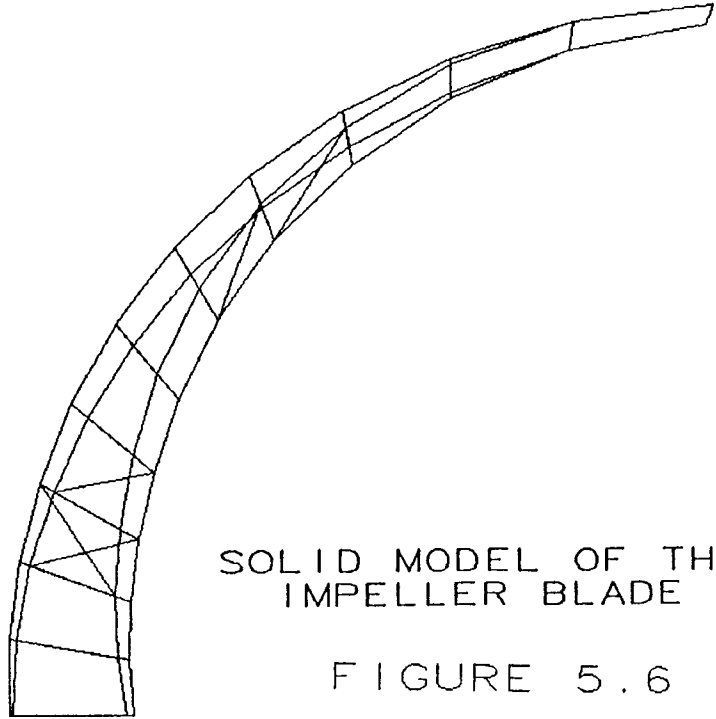
FIGURE 5.4



SKIN GROUPED PROFILES
OF THE IMPELLER BLADE
VIEWED FROM DIFFERENT ANGLES

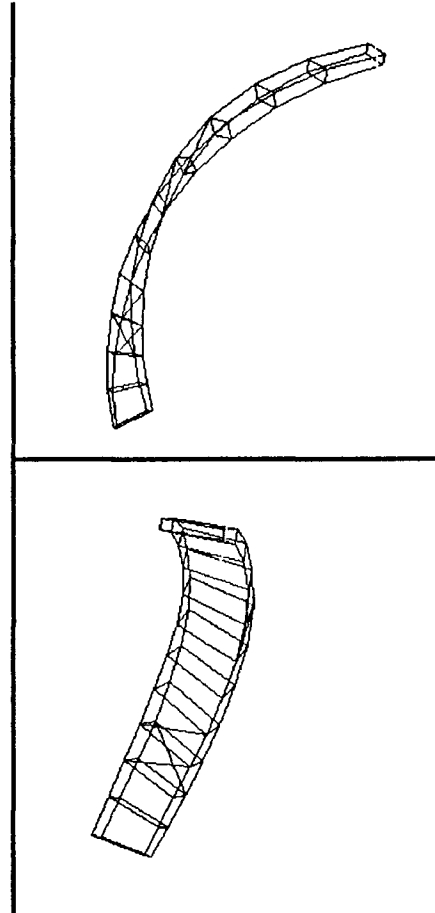
FIGURE 5.5

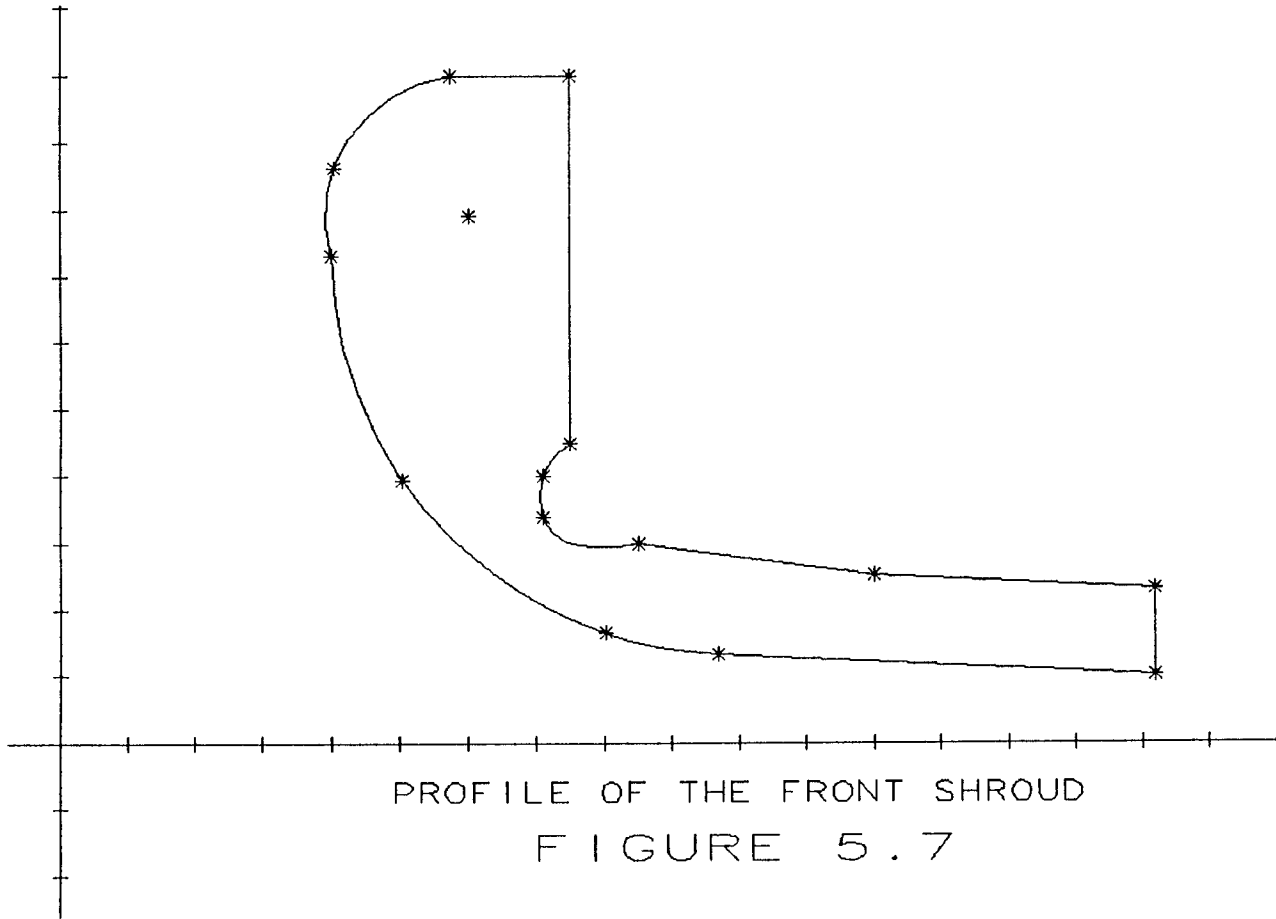


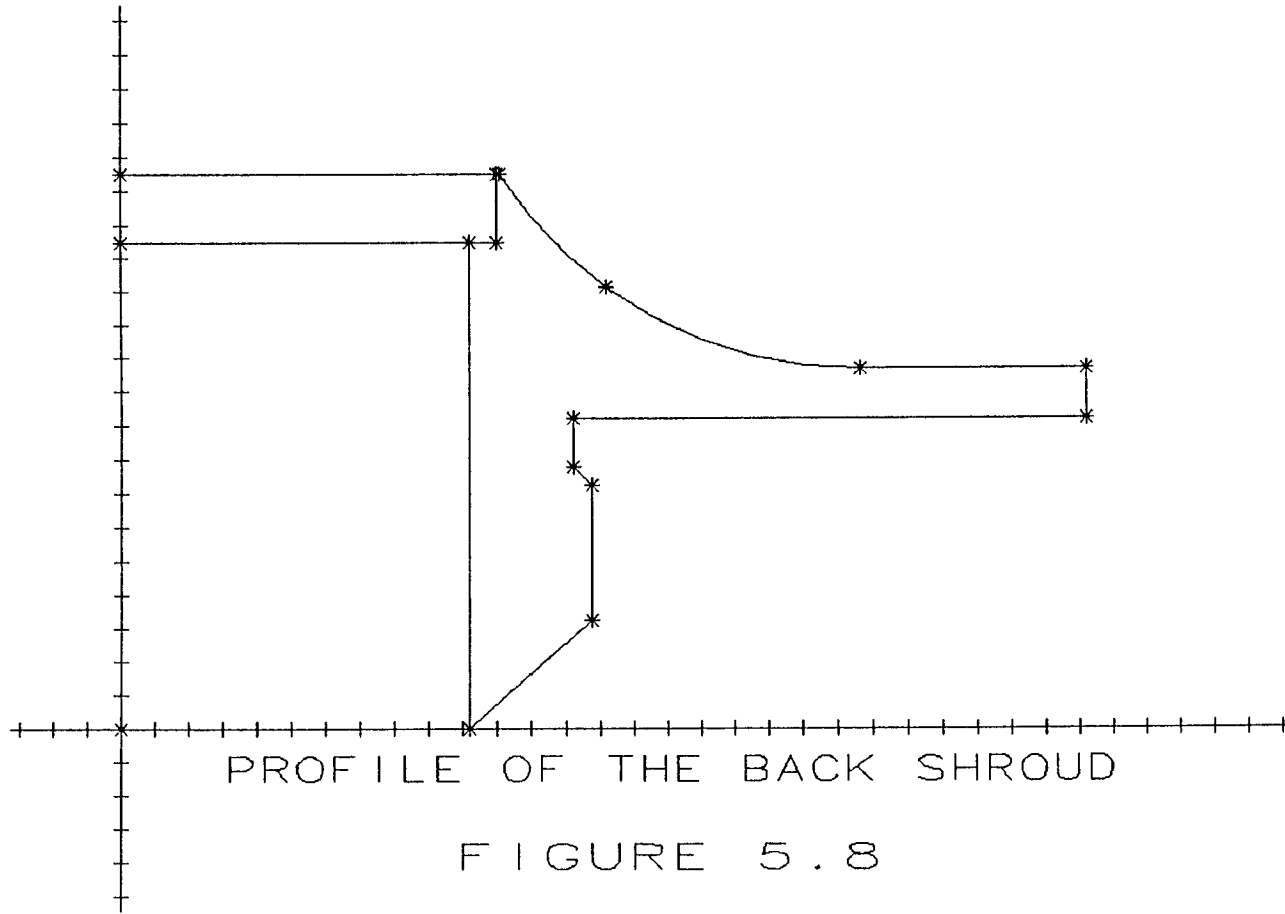


SOLID MODEL OF THE
IMPELLER BLADE

FIGURE 5.6

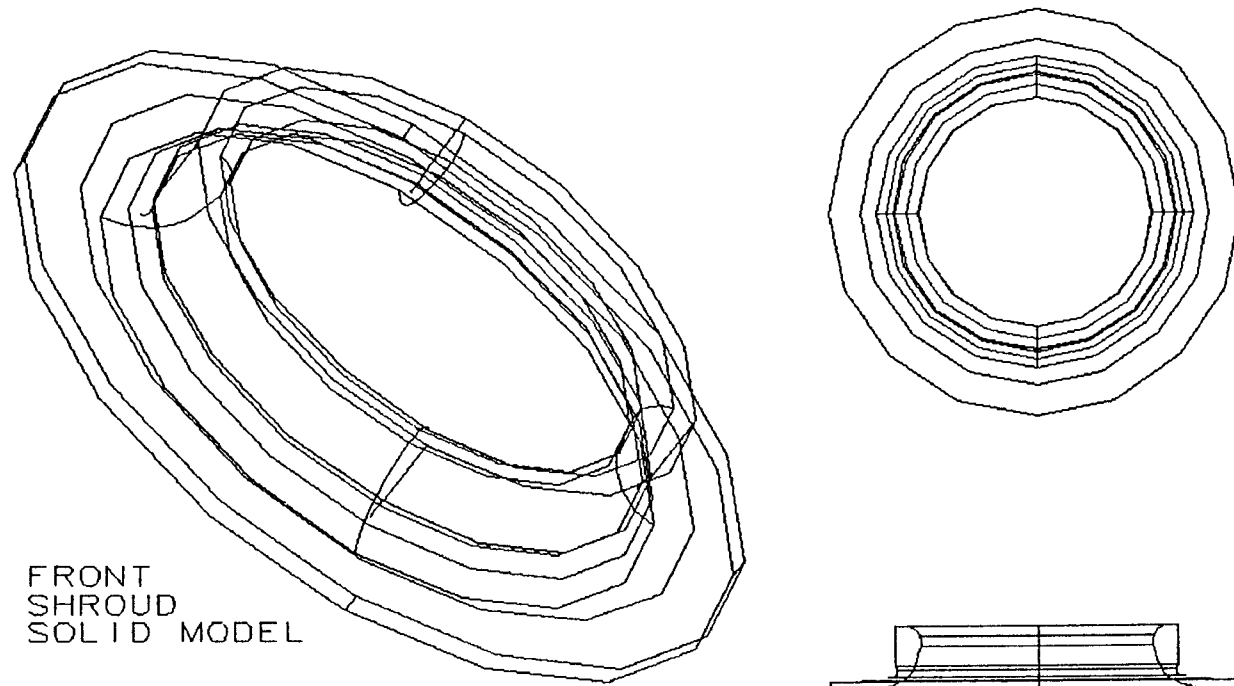






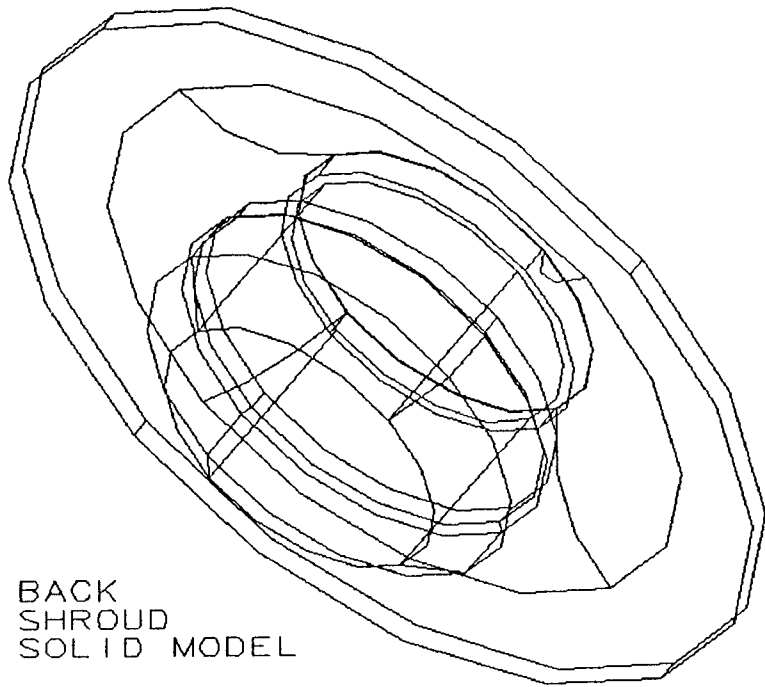


SOLID MODEL OF THE
IMPELLER BLADE
FIGURE 5.9



FRONT
SHROUD
SOLID MODEL

FIGURE 5.10



BACK
SHROUD
SOLID MODEL

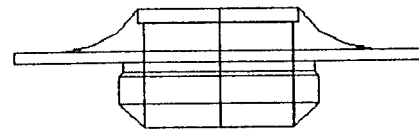
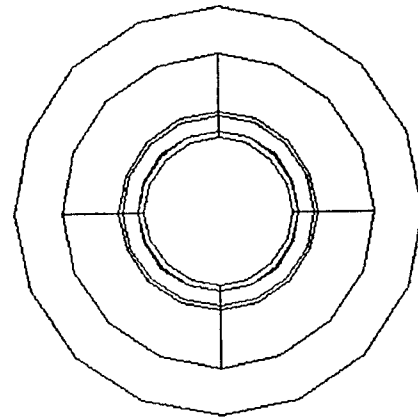
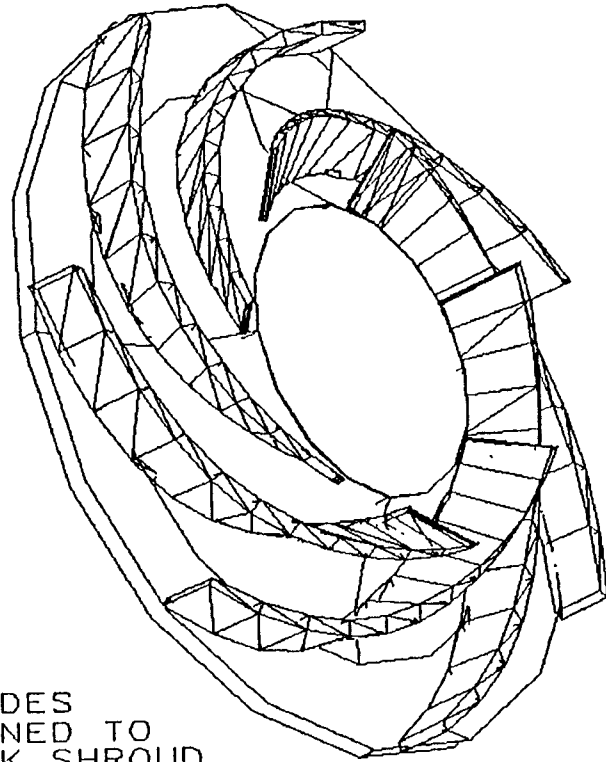


FIGURE 5.11



BLADES
JOINED TO
BACK SHROUD

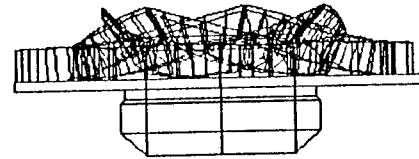
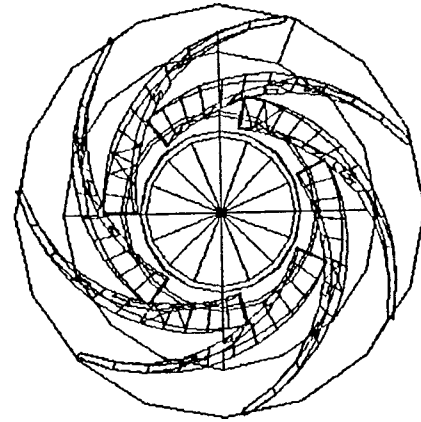


FIGURE 5.12

iv) Triangulation of the facets

The objects were retrieved and their facets were triangulated, because in order to convert the files into .STL format the objects must have a triangulated facets.

v) Joining the objects

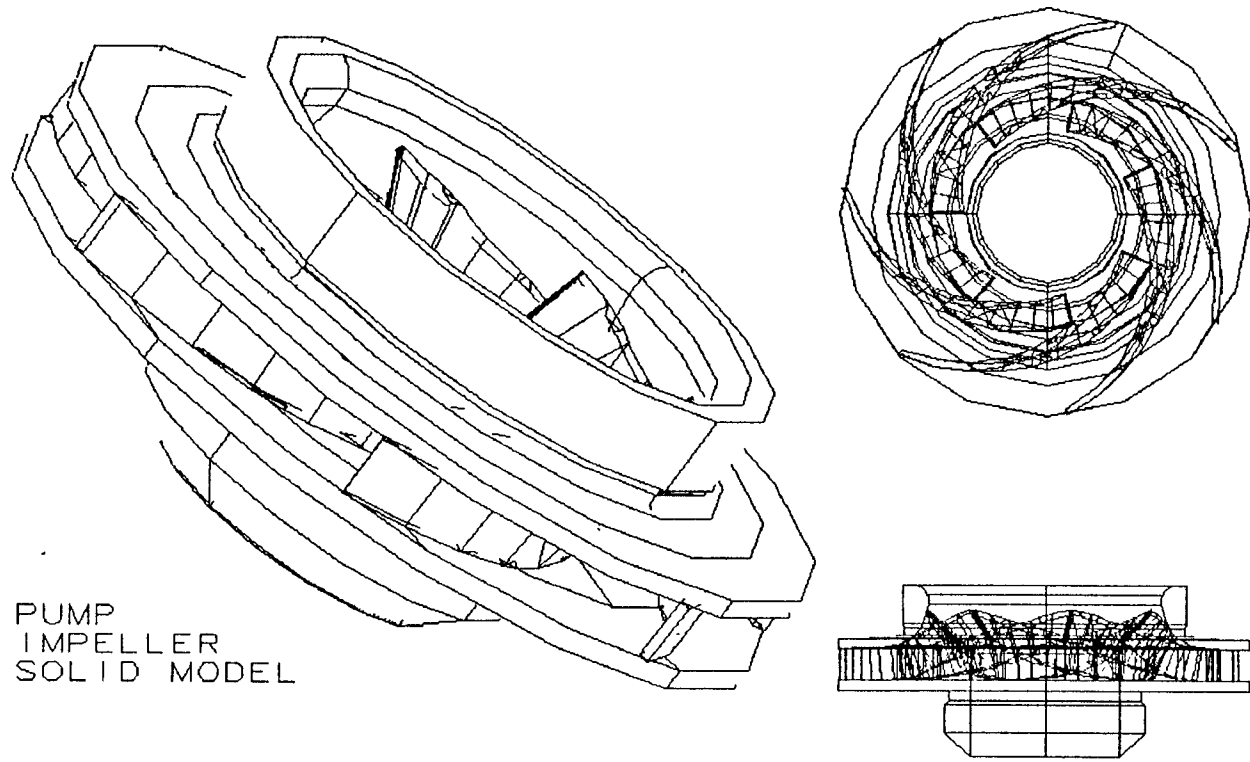
The objects stored again after triangulation, are ready to be joined. This comprise of three steps:

one- The backshroud was brought on the workbench and then the single blade was retrieved on the screen.

two- Both of the objects were oriented in proper position so that their faces and angels exactly represent the desired values.

three- The two objects were then joined by using "join" command, in the "construct" option of the object modeling task. The blade was retrieved in the same manner, oriented, rotated and joined to the backshroud as shown in figure 5.12.

Finally the front shroud is retrieved on the screen and is joined to the backshroud containing blades, thus forming the complete impeller assembly (figure 5.13). (for color prints of the impeller see appendix).



PUMP
IMPELLER
SOLID MODEL

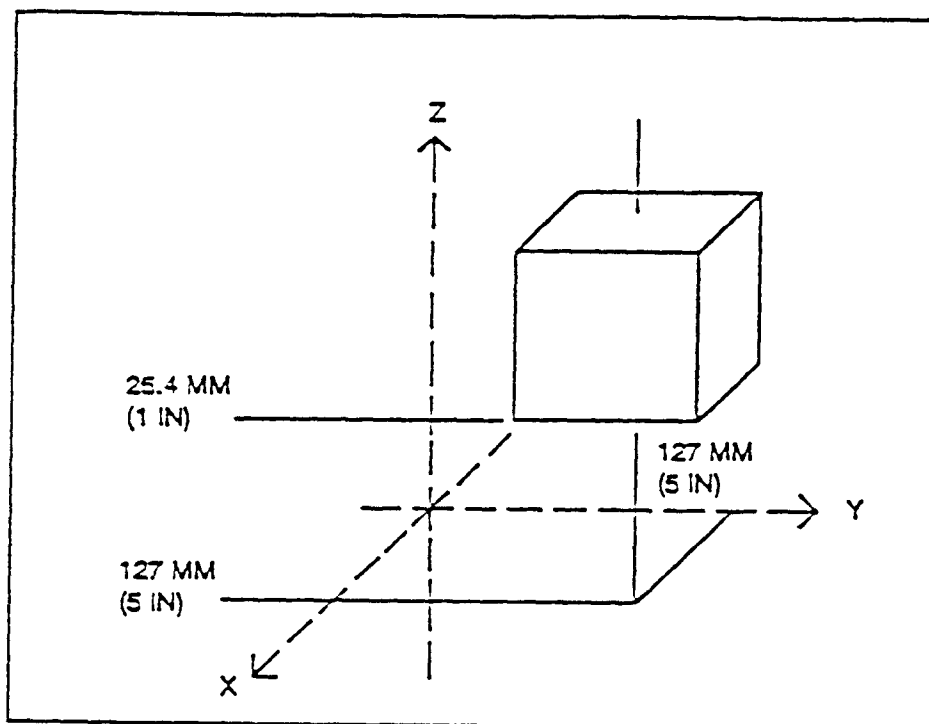
FIGURE 5.13

Step 2 - Orient and Support

The model created was larger than the available space in the vat, i.e ten-inch cube, therefore it was scaled down 33.33% to fit into the machine, it was then oriented properly, as each object must reside entirely in the positive X,Y,Z octant of the CAD space (fig 5.14). A support structure is then added to hold the part in place while the layers were being built, to maintain layer registration and the structural integrity of the part.

The object was oriented to

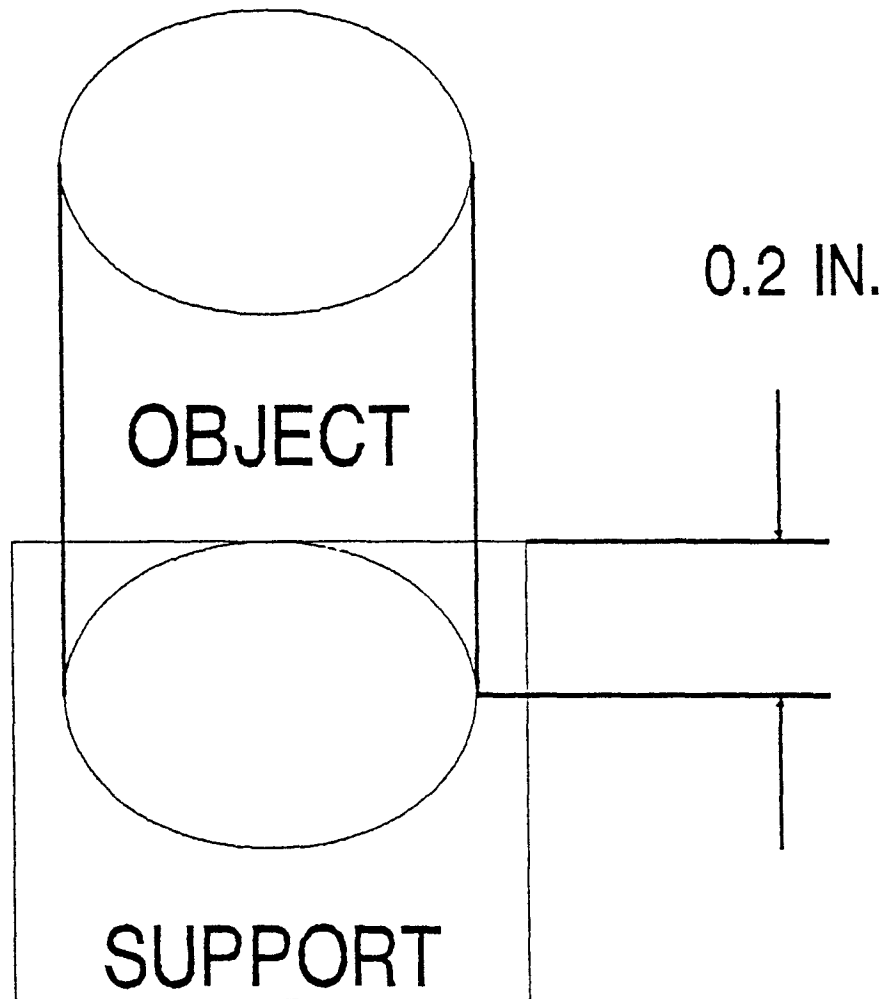
- * Minimize the distance between the part and the CAD origin.
- * Minimize the height of the support structure. The part is kept 0.2 inches above the platform for efficient draining (figure 5.15). However, supports that are too tall take longer to build and may distort as the weight of the part increases while it is being built.
- * Minimize the height of the object. This reduces the number of layers to be built, thereby reducing the build time.
- * Optimize part draining by reducing the number of areas (trapped volume) that can hold resin after the part is completed.



CAD Model in Positive X, Y, Z Octant

Figure: 5.14

STEREOLITHOGRAPHY



Object and Support positioned
for efficient drainage

Figure 5.15

Recommendation

It is recommended that all parts are sliced on the Z-axis to avoid confusion, and to simplify any offsetting required in merge.

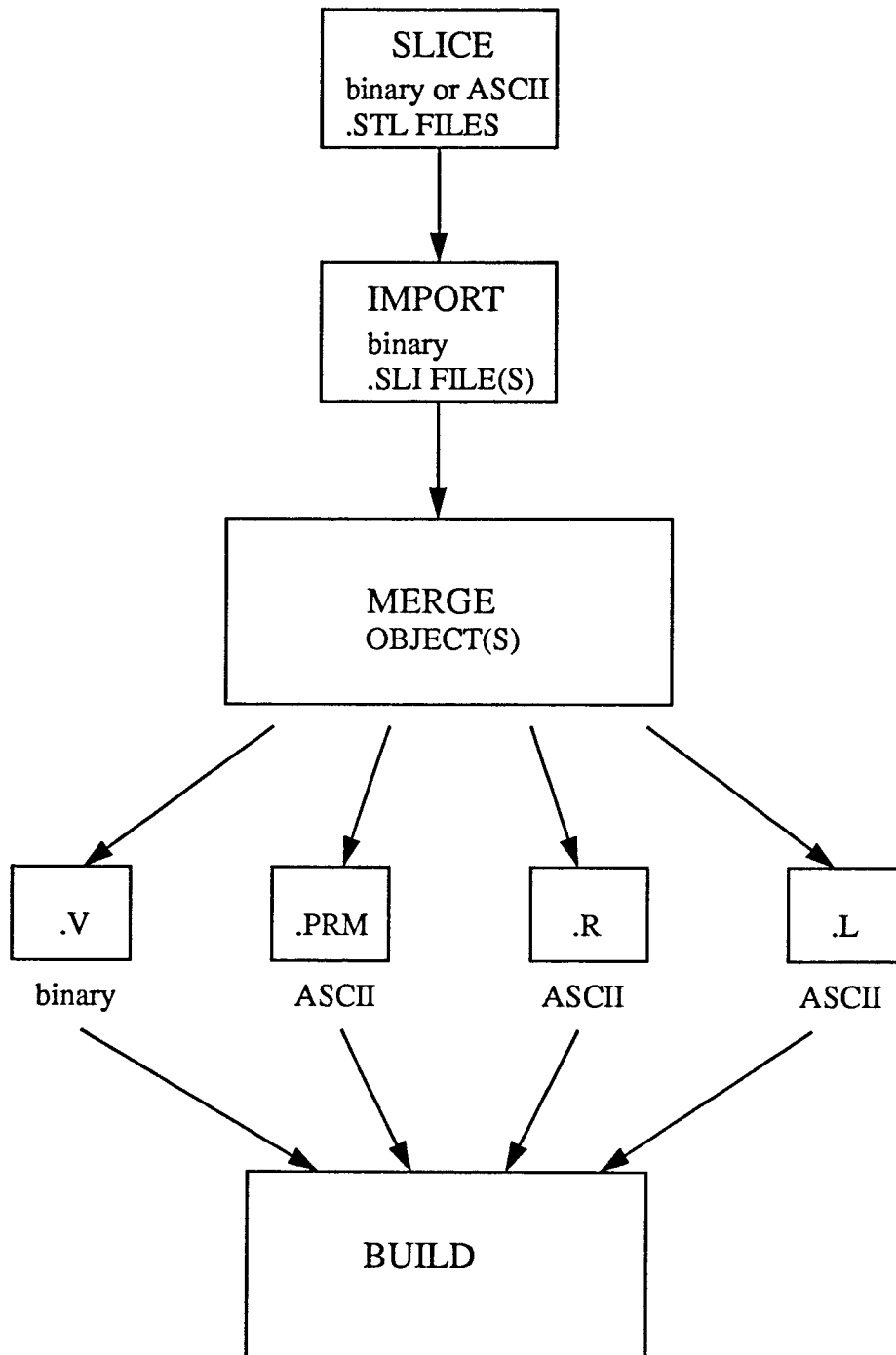
Step 3 - CAD Interface

The I-DEAS package provide us with many interfaces which include the Rapid prototyping interface also, therefore by following the steps as under, the part is converted to a format similar to a finite element model consisting of triangular surface elements or patches. The output from this process is a StereoLithography (.STL) file:

- * Selecting "families" option from the "task" menu.
- * selecting "interfaces" from "families" menu.
- * selecting "Rapid prototyping"
- * Then selecting "create prototype"
- * after which "SLA-250" was selected
- * After which computer asks for bounding box min. limit, providing the value, finishes the process and a .STL file is created in the directory.

5.3.2 SLA Stage

Using the StereoLithography Apparatus, the next six steps process the object and support data and control the part building process. The basic part preparation data structure is shown in figure 5.16



Basic Part Preparation Data Structure

Figure: 5.16

Step 4 - Slicing

Using a sophisticated, proprietary algorithm, each file was sliced into cross sections, typically between 0.005 to 0.0020 inches (.12 to .50 mm). The thickness of each layer could be varied through out the part. In this experiment it is kept constant. In addition, the creation of the internal crosshatch structure between inner and outer surface boundaries (vertical walls) could also be controlled. In the experiment it was kept 0.25 inch. This serves to support the vertical walls and entrap liquid which will later be solidified with a flood of UV light. Horizontal "skins" for top and bottom surfaces were also created. The output file from the slice computer (Limbo at NJIT) is .SLI file.

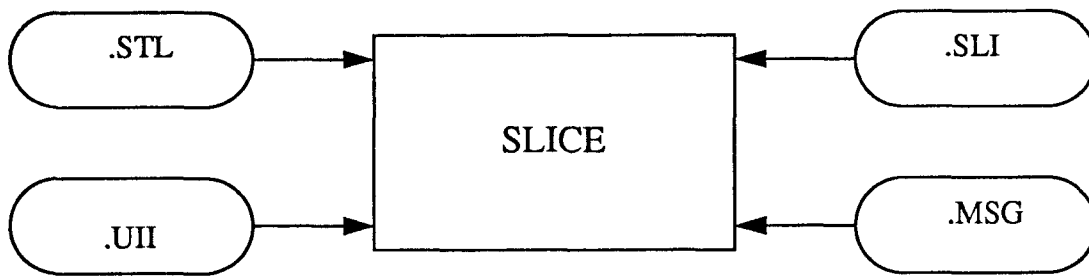
During the Slice process, the slice program reads in an .STL file and a .UII file and writes out a slice (.SLI) file and a message (.MSG) file, which is shown in figure 5.17.

Step 5 - Networking:

After slicing the part, database was transferred to the control computer which is attached to the SLA apparatus. The transfer of the database was accomplished through local area network.

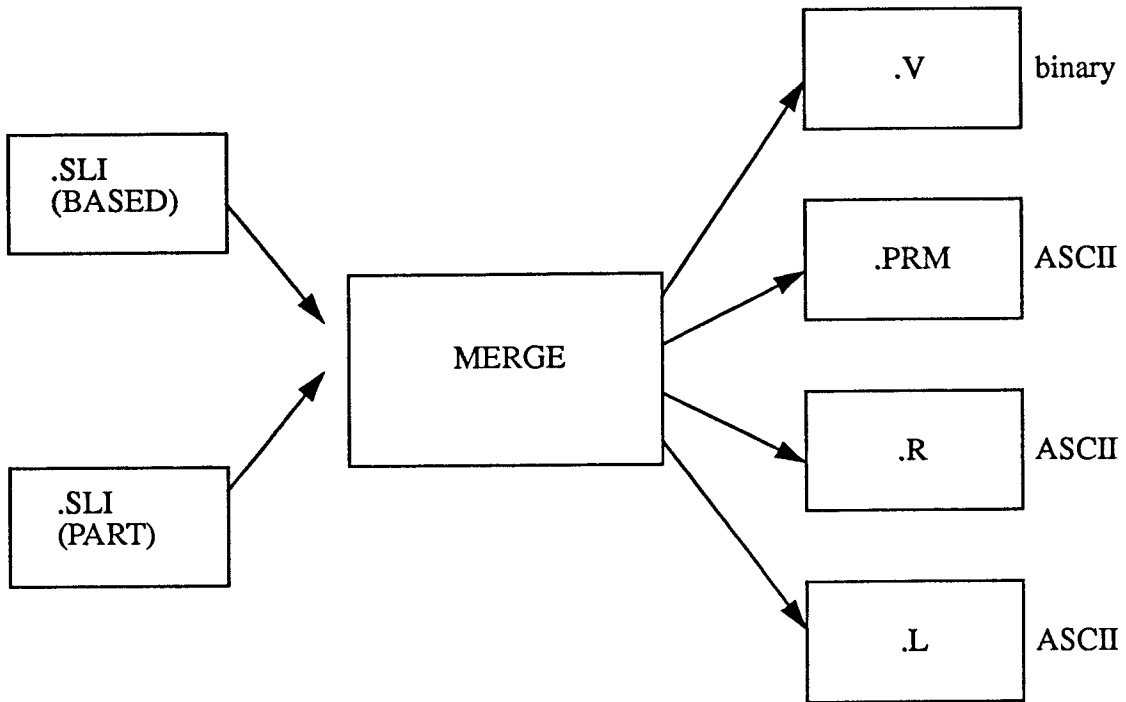
Step 6 - Merge

For each object or subsection of the part, a separate support structure is needed, which helps in anchoring unattached layer sections and also prevents deformation of



Slice Process

Figure: 5.17



The Merge Process

Figure: 5.18

the extended portions. Therefore the objects (support and part) are combined into one build part database, or merged. In this process, the data is reformatted into SLA machine code contained in four separate files as shown in fig 5.18:

- 1) Vector file (.V)
- 2) Range file (.R)
- 3) Layer file (.L)
- 4) machine Parameter file (.PRM).

Step 7 - Utility Setup

After the files were transferred to the control computer and the merging is done, the laser power was measured and the SLA was initialized and set up to build parts. A platform was attached and lowered into the vat filled with liquid resin.

Step 8 - Preparing

Before starting the construction of the part, building parameters, including the amount of adhesion between layers, and the number and location of parts (object and support) to be built as well as recoating parameters based on the model's geometry and end use were set. Each phase of the part building can be customized by varying building parameters within vertical ranges.

Step 9 - Building

The resin level was adjusted by adding photopolymer. Then the Build software was activated to control the part building process which creates one layer at a time by moving a focused laser beam across the surface of photo curable resin, solidifying the liquid where it strikes.

The laser draw the first cross section, which adheres to the platform. When creating each cross section, the inside and exterior boundaries are solidified along with the internal crosshatch. Resin was then trapped between the solid areas, as the object was building up. The elevator dips below the surface, coating the cross section with resin, and a recoater system maintains the correct amount of liquid on top of the previous cross section. The second layer is drawn and becomes firmly attached to the first.

This process was repeated until all layers have been drawn to form the three-dimensional centrifugal impeller model. When the part was completed, the trapped liquid still requires the ULTRAVIOLET exposure to become a final solid model.

When the complete impeller was being build, the design facility of the SLA to operate round the clock was used, and the machine was left unattended during the process. After the last layer was printed, the completed part was raised out of the vat. The building time was automatically logged into a history file and the laser was powered off. An on time was scheduled less than four hours.

5.3.3 PCA Stage

The last step uses the Post Curing Apparatus.

Step 10 - Post Processing

The part, after building has been completed, requires final ultraviolet curing. To do so, first the part was raised out of the vat and excess liquid was drained off the part. The remaining excess liquid is usually removed with solvents, ultrasonics or wicking. In this case ultrasonics process was used. The part was then placed into the PCA to undergo several exposures. The part was later removed from the platform and the support structure was clipped from the part. Finishing techniques, such as sanding, sandblasting, painting, or dyeing, was than applied.

CHAPTER 6

APPLICATIONS AND BENEFITS OF DTM SYSTEMS

Desk top manufacturing systems can produce models in much less time than conventional methods. Parts that take days weeks or months before being produced, can be prototyped in matter of hours, with the use of Desk top manufacturing systems.

6.1 Applications

6.1.1 Design Engineering

* Conceptual design models are used widely throughout a variety of industries, including: automotive, aerospace, medical, computer, electronic, and consumer products.

* By quickly forming three-dimensional conceptual models from design ideas, engineers can evaluate a design, demonstrate its feasibility and sell the concept.

* "What if" scenarios can also be quickly evaluated to iterate a design toward an optimum.

* Up-to-date design review prototypes provide for a quick understanding of the state of the current design, resulting in valuable feedback.

* The physical model can be used to check the form of a part, such as the new styling for an automobile part, or industrial design of consumer product.

* Fit can be verified by placing or assembling the prototype with other components in a subassembly, checking clearances, and identifying interference problems.

* Function tests can range from aerodynamic testing in wind tunnels to using the model in human engineering studies.

* The impact of changes in other related components can also be quickly studied.

* CAD/CAM/CAE databases, now gaining popularity as the primary definition of the product can also be verified, since the data is used directly to create the part. In addition, the important and time consuming task of verifying engineering changes can be facilitated.

6.1.2 Manufacturing Engineering Link

* Desk top manufacturing aids in the link between engineering and manufacturing, allowing for optimizing the part for function, while simultaneously reducing manufacturing costs and schedules for example figure 6.1 shows the design changes are less expensive in the early stage

COST OF DESIGN AND ENGINEERING CHANGES

Using the SLS Process, design changes can be made earlier in the cycle, when they are less expensive to make.

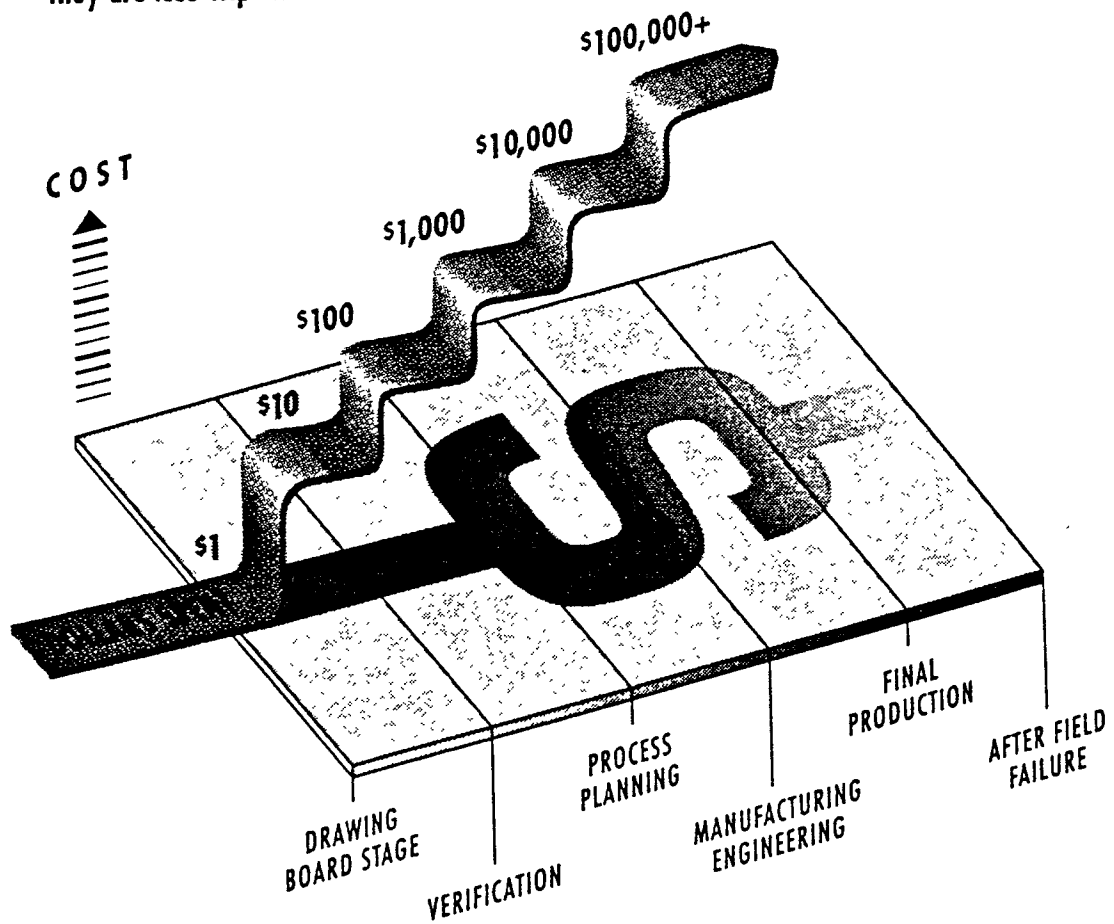


Figure: 6.1

of the design cycle, here SLS process is representing a DTM technique.

* Producibility studies can utilize the prototype to provide valuable input earlier in the design process. This could reduce assembly time or eliminate unnecessary tooling or machining.

* By accurately describing complex geometry, parts made by DTM can help contract shops bid on jobs and reduce problems with interpreting engineering drawings on the shop floor.

* Visualizing the final product also assists the design of tooling on a CAM system, as well as aiding in programming tool paths and optimizing machine set up and tool changes.

* Models can also be used to convey complex design geometry and formulate manufacturing production process and tooling.

* Prototypes, especially with intricate internal detail, can also be used as master patterns for casting.

6.1.3 Concurrent Engineering

Concurrent engineering is the key word in product development for the 1990's and into the twenty-first century. Concurrent engineering involves the use of a single data base from design engineering to manufacturing to

quality control. The rapid prototyping methods can very effectively support and facilitate the concurrent engineering process based on the strength of the data base used to drive the system.

Rapid prototyping is also creating a reliance on CAD data and diminishing the need for design drawings. The creation of the CAD file allows the designer the experiment with multiple design changes. After the product design is finalized, the data base is used to produce a hard model.

This hard model, using the qualified designed data, may have multiple functions in the product development process: it may be used to create a tool to cast a urethane part, it can be input to get a model for engineering testing and U.L certification, and it may be used to drive CNC machine tools.

Along with the general applications explained above there are many other applications of the individual systems such as

6.1.4 Applications of SLA

There are many applications of this process but it has some disadvantages, which make it a little restricted.

Advantages:

i) The biggest advantage is that the computer generated design may be turned into a solid model in very short time, the part can be viewed, studied, tested and compared.

ii) No operators attention is required once the process is started.

iii) Several models can be made in one setup.

Disadvantages:

i) Polymers are expensive as compared to other DTM process materials.

ii) Surface finish is not good. Models are usually rough because the building process involves the fusing of layers.

iii) Fine tolerancing cannot be produced.

iv) Materials usually used are toxic.

6.1.5 Applications of SLS

The numerous advantages of this process make it suitable for a broad spectrum of design verification applications. In fact, new uses for this adaptable technology are continually emerging. Most commonly the SLS process is used to generate:

a) Conceptual models (or physical models) Three dimensional versions of designs that are reviewed for form only.

b) Functional models - Sample parts that can be tested for function and fit within assemblies.

c) Patterns and molds - Objects that can be used to manufacture durable prototypes with the process and material of choice.

d) Short-runs - Small quantities of parts that can be used for end-use applications.

6.1.5.1 The SLS Process Applied to Investment Casting

Unlike most rapid prototyping technologies currently available, the Sinterstation 2000 System has been used effectively to streamline the creation of wax patterns used in the investment casting process.

In fact, the SLS process and wax pattern - making are extremely well matched for several reasons.

a) Exclusive use of wax

The SLS process is currently the only rapid prototyping process that can utilize investment casting wax to make very complex wax patterns for investment casting.

b) Accuracy

With the current capability to achieve average tolerances ranging from +/- 0.005 to +/- .015 inches, the SLS process offers the accuracy required by most investment casting applications.

c) Complex geometries are easily created

The SLS process can easily create complex shapes and geometries, which might be difficult, expensive, or time-consuming to produce via other methods such as machining and prototype tooling.

d) Surface finish

Wax patterns created with the SLS process feature a surface finish suitable for most investment casting applications. This surface finish is typically 100 to 120 average micro inches RMS or less on the sides and 50 micro inches RMS or less on the top surface.

6.1.6 Applications of FDM Process

The 3 dimensional model, created through Fused Deposition Method is so accurate that it could be used in the spray metal process for injection molding. The filament materials used by Stratasys have the durability and stability required of a master for spray metal molding.

This technique has been applied from the simple casting of urethane in the shoe industry to injection molding of glass filled resins. These glass filled resins are used for high strength, heat and wear resistant parts such as photo equipment, small power tools and appliances.

6.1.6.1 Casting Applications of FDM

The FDM process is ideal for other mold making and casting processes. For example, users of silicon, rubber and epoxy molds can use the prototype as a manufacturing master. The FDM model serves as a fast, easy way to create prototypes and low volume prototype tooling.

6.2 Benefits

6.2.1 Design Optimization

One of the main benefits of using Desktop manufacturing systems is the fast turn around time for conceptual models - hours instead of the conventional weeks or months. Design review cycles can also be reduced by evaluating the three-

dimensional design instead of studying engineering drawings.

6.2.2 Product Quality

Form, fit and function tests can be performed much earlier in the design cycle with a physical model, reducing the number of costly engineering change orders issued after the product has entered production. This can reduce the amount of lost production time, re-tooling, rework, and scrap waste incurred in manufacturing. A physical model can reduce errors from incorrect interpretation of the design.

6.2.3 Speed

Many traditional prototyping methods require weeks, and some times months, to produce a single prototype part. This is especially true where complex geometries are involved as in our case for the centrifugal pump impeller.

In contrast by using desktop manufacturing systems the same work could be done in a fraction of time, a complex part, like the impeller could be made in matter of hours. Current statistics reveal that the most of the DTM processes can produce objects at a rate of one-half to one inch per hour.

A four inch part, for example, can conceivably be completed in four to eight hours, depending on the complexity of the part geometry.

Access to this exceptional technique, can significantly step up a company's product development cycle, saving weeks and even months of development time. This in turn can help move the final product to market faster, or it can provide additional time to refine a complex or critical design.

6.2.4 Simple or Complex part manufacturing

In most of the desktop manufacturing systems, the 3-D part is created layer by layer. this characteristic allows for production of prototypes and parts featuring virtually any shape or geometry.

For example, notches within notches, overhangs, hollowed areas, and other complex features that are often difficult to fabricate with other prototyping methods, are produced easily with the DTM systems.

6.2.5 Risk Reduction

Prototyping methods that require tooling can be risky, expensive, and time-consuming. This is because tooling must usually be done before a design has been reviewed and verified in 3-D form.

Using DTM techniques, three-dimensional prototypes can be created and refined without the risk, expense, and time associated with prototype tooling. In fact, by the time any tooling is required, the design has typically been verified. Any required corrections or adjustments to the design will have already been made.

6.2.6 Time To Market

With conceptual three-dimensional models, designs can be finalized much faster. Producibility requirements can be brought into the design process before a commitment to one design is made, reducing manufacturing costs. Utilizing the plastic part, production tooling design times can also be reduced.

6.2.7 Benefits to Investment Casters

The DTM processes offers numerous benefits to investment casters, for example:

6.2.7.1 Through SLS

- * SLS Provides a faster path to the creation of metal parts,
- * Eliminates the time and expense associated with traditional prototype tooling,
- * Can be used in short-run manufacturing.
- * Offers a way to produce parts with complex shapes and geometries,
- * Enables concurrent tooling, and
- * Aids in process development by allowing for the rapid evaluation of gating schemes and shrinkage factors.

6.2.7.2 Through FDM

The Fused Deposition Modeling method eliminates the multi-step investment casting process for complex metal components. The time-consuming step of producing wax replica

of the part to be manufactured is eliminated. The desired part created in Stratasys' investment casting can be dipped directly into the ceramic slurry. The wax pattern then quickly dewaxes from the ceramic shell when fired.

Another major problem with the investment casting of complex geometries is the prediction of shrinkage of the cast metal part. With the FDM process one can build an initial model with the calculated shrink, invest the wax then cast the part. If changes are needed, another model can be readily built with the shrink rate modified.

A number of models can be built after being scaled to accommodate various shrink factors and cast at the same time. The investment cast prototypes can then be checked and compared. After the right shrink is determined, another FDM model is built, a spray metal mold is constructed from it and a number of prototype parts can be cast.

CHAPTER 7

ANALYSIS, COMPARISON AND CONCLUSIONS

7.1 Experimental Analysis

Most of the major scientific developments are the results of experimental analysis performed in various fields of study. In this thesis experiments are also conducted in order to achieve some analytical results. Efforts were made to determine the various effects of using Desk Top Manufacturing systems as compared to the conventional prototyping methods.

Building a prototype of a centrifugal pump impeller on a SLA-250 machine was the first step of the analysis, the data for which was provided by a well known pump manufacturing company. The pump has a complex geometry and is difficult to cast and almost impossible to machine. While using a rapid prototyping method known as StereoLithography (SLA), it took a fraction of time and money to build.

Experiments were designed to provide some comparative data between DTM systems SLA and SLS, and conventional machining methods.

7.1.1 Assumptions for the Experiments

* The numerical values used in the analysis are rounded to the nearest integer to attain smooth curves on the graphs.

- * All of the data for the conventional method of building the prototype of the pump impeller is either multiplied or divided by a constant number to hide the actual values, on the request of the company providing the data.
- * Dimensions of the part is scaled down to fit the SLA machine.
- * Cost is kept in units of hundreds or thousands, for the sake of compatibility of the data with other parameters.
- * The experiments performed were quite expensive and funds were limited, therefore, the readings were restricted to no more than five.

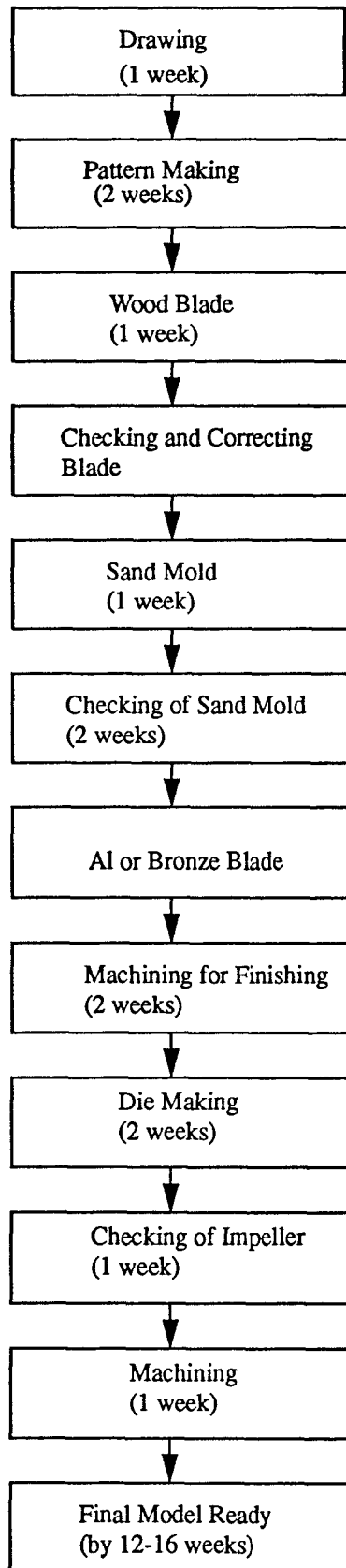
7.2 Analysis of the Results Obtained

7.2.1 Process Comparison on the basis of COST

Sand casting vs SLA:

The comparison is made among the Sand casting design cycle of the centrifugal pump impeller (figure 7.1) and the DTM design cycle on SLA (figure 7.2). The data used, was provided by the pump manufacturers and other readings taken from the SLA-250 available at NJIT campus (table 7.1).

The graph (figure 7.3) shows the process involved for actual casting of the pump impeller costs about 50 times more than the model made on SLA. It is also clear how the number of steps are reduced due to the use of the SLA process.



SAND CASTING
DESIGN CYCLE
OF THE
CENTRIFUGAL
PUMP IMPELLER

Figure: 7.1

DTM DESIGN CYCLE
ON SLA OF CETRIFUGAL
PUMP IMPELLER

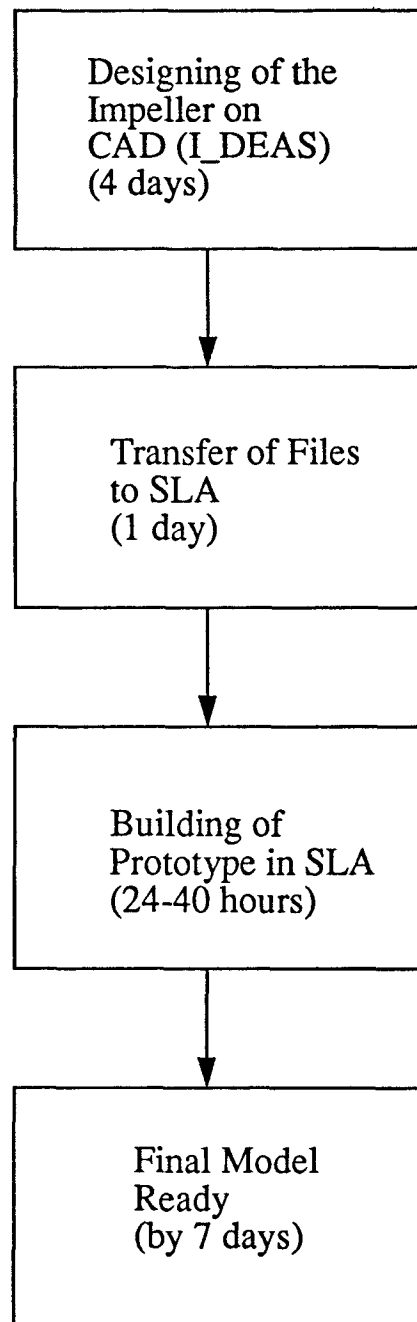


Figure: 7.2

**EXPERIMENTAL DATA OF CENTRIFUGAL PUMP IMPELLER
FOR COST COMPARISON OF
SLA VS SAND CASTING**

PROCESSES X DATA	COST IN DOLLARS	
	SLA SERIES 1	SAND CASTING SERIES 2
DRAWING	300	200
PATTERN	100	4000
WOOD BLADE	-	1000
MOLD	-	2000
AL BLADE	-	3000
DIE	-	5000
FINAL PART	400	21300

TABLE NO: 7.1

COST COMPARISON SAND CASTING vs SLA

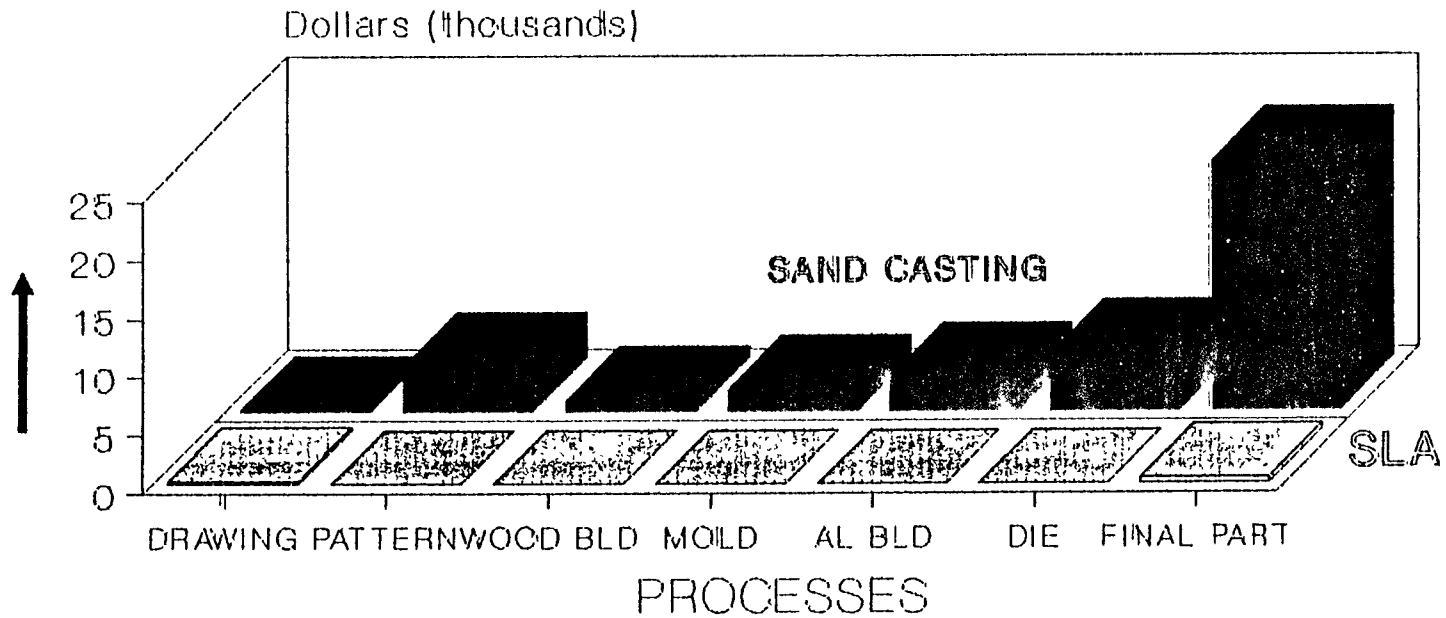
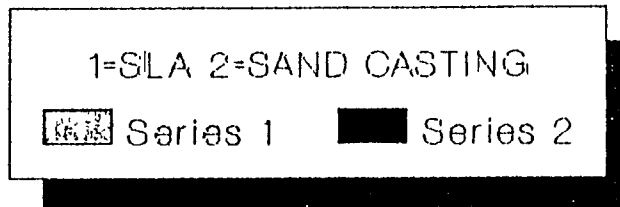


Figure: 7.3



7.2.2 Process Comparison on the basis of TIME

DTM system vs Conventional Investment casting:

The data from table 7.2, after analysis, shows that the time for the conventional investment casting cycle for the same part building is 12 times more as compared to a Desk Top Manufacturing system graph (figure 7.4).

7.2.3 Process Comparison on the basis of QUANTITY

SLA vs Conventional tooling:

The graph (figure 7.5) based on the data shown in table 7.3 reflects the results. After observing a number of parts being manufactured it was analyzed that the cost of making a part on SLA machine is directly proportional to the number of parts being manufactured in a batch. Where as for conventional tooling the case is different. There the cost after increases to a certain level becomes stagnant. It shows that the fixed cost, including over heads, remains constant for a certain batch size, keeping the over all cost constant.

7.2.4 Process Comparison on the basis of COMPLEXITY

For this analysis three different methods were selected, two representing DTM manufacturing techniques, while the third one is a conventional CNC operation.

The graph (figure 7.6) clearly shows that, as complexity of a part increases the cost of fabrication

**INVESTMENT CASTING DEVELOPMENT CYCLE
DTM SYSTEM VS CONVENTIONAL**

PROCESSES X DATA	TIME IN DAYS	
	DTM SERIES 1	CONVENTIONAL SERIES 2
DESIGN PART	2	7
PATTERN	3	14
MOLD	0	14
DIE MAKING	0	20
FINAL PART	5	55

TABLE NO:7.2

INVESTMENT CASTING DEVELOPMENT CYCLE DTM SYSTEM VS CONVENTIONAL

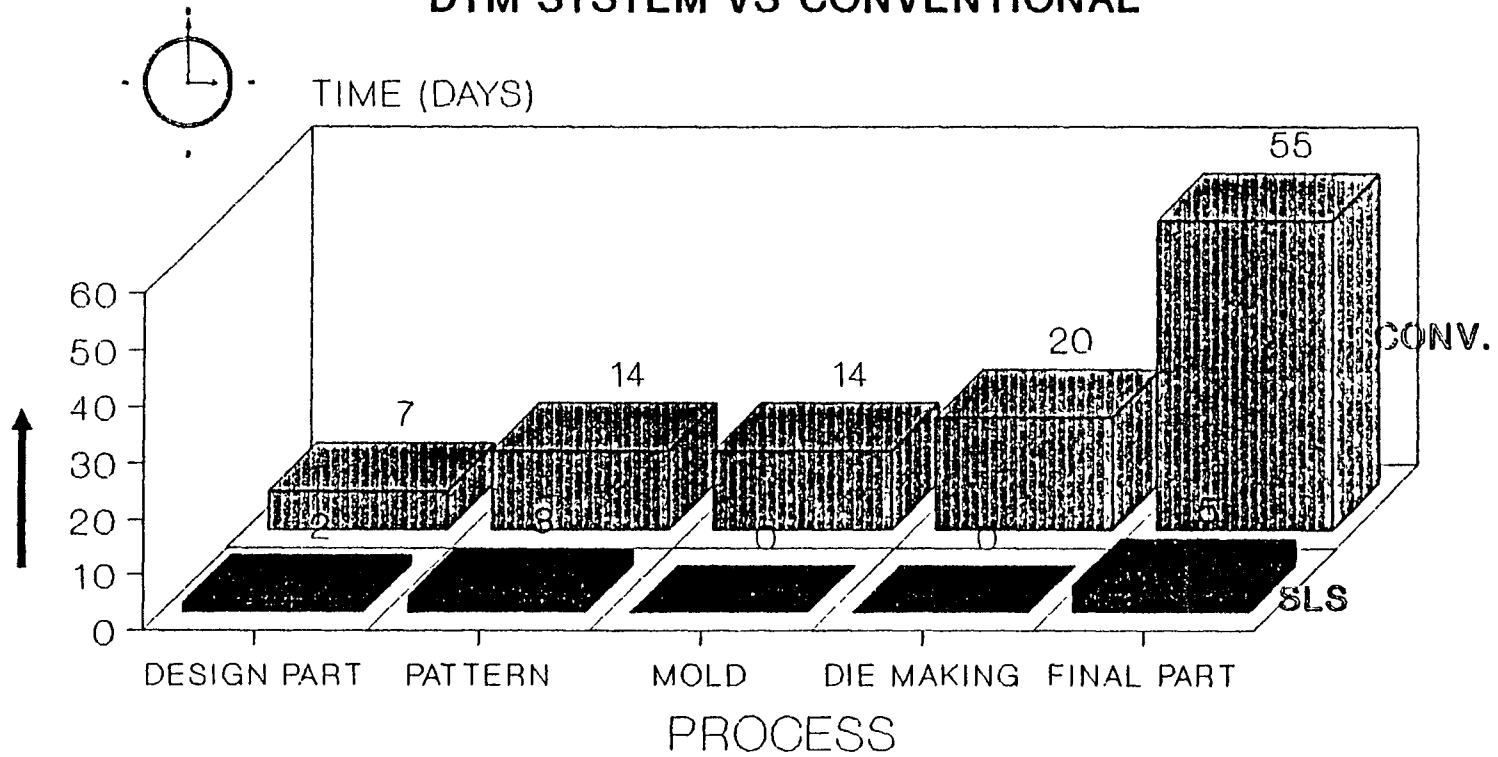
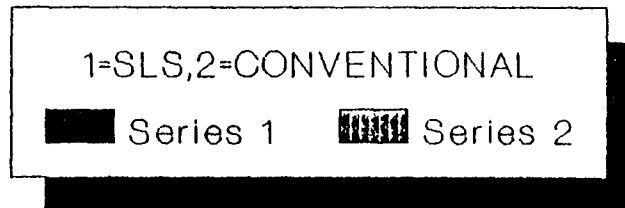


Figure: 7.4



COST QUANTITY COMPARISON
SLA VS CONVENTIONAL TOOLING

QUANTITY IN UNITS X DATA	COST IN THOUSANDS OF DOLLARS	
	SLA	MOLDED PATTERN
	SERIES 1	SERIES 2
0	0	0
10	4	8
20	8	8
30	12	8
40	16	8
50	20	8
60	24	8
70	28	8
80	32	8
90	36	8
100	40	8

TABLE NO: 7.3

COST QUANTITY COMPARISON SLA VS CONVENTIONAL TOOLING

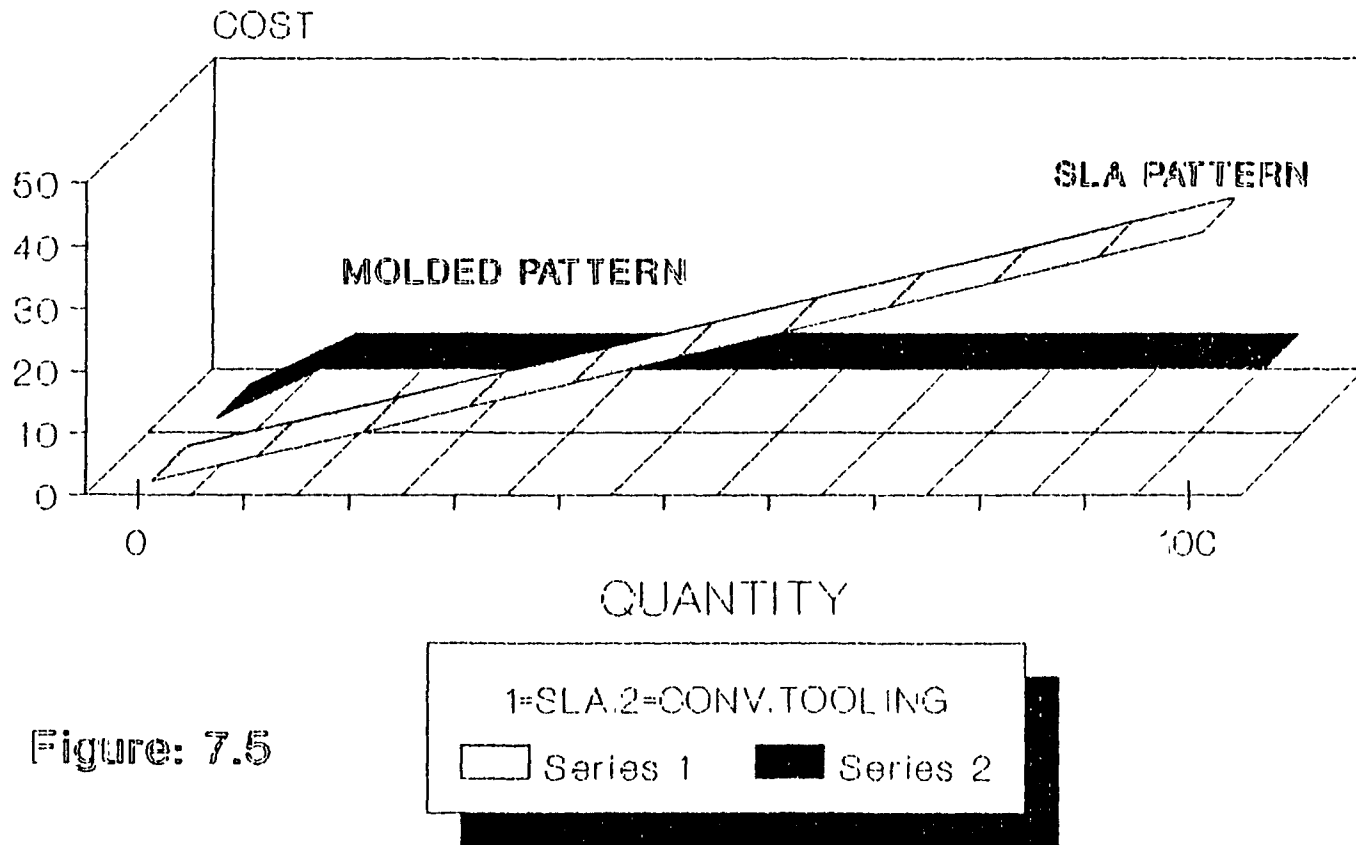


Figure: 7.5

**TECHNOLOGY PRICE PERFORMANCE
DTM SYSTEMS VS CNC**

COMPLEXITY X DATA	COST IN HUNDREDS OF DOLLARS		
	CNC SERIES 1	SLS SERIES 2	SLA SERIES 3
SIMPLE GEOMETRIES	1	4	4
	10	6	6
	20	8	8
	30	10	10
	40	12	12
	50	14	14
	16		
COMPLEX GEOMETRIES		18	
		20	

TABLE NO: 7.4

TECHNOLOGY PRICE PERFORMANCE

DTM SYSTEMS VS CNC

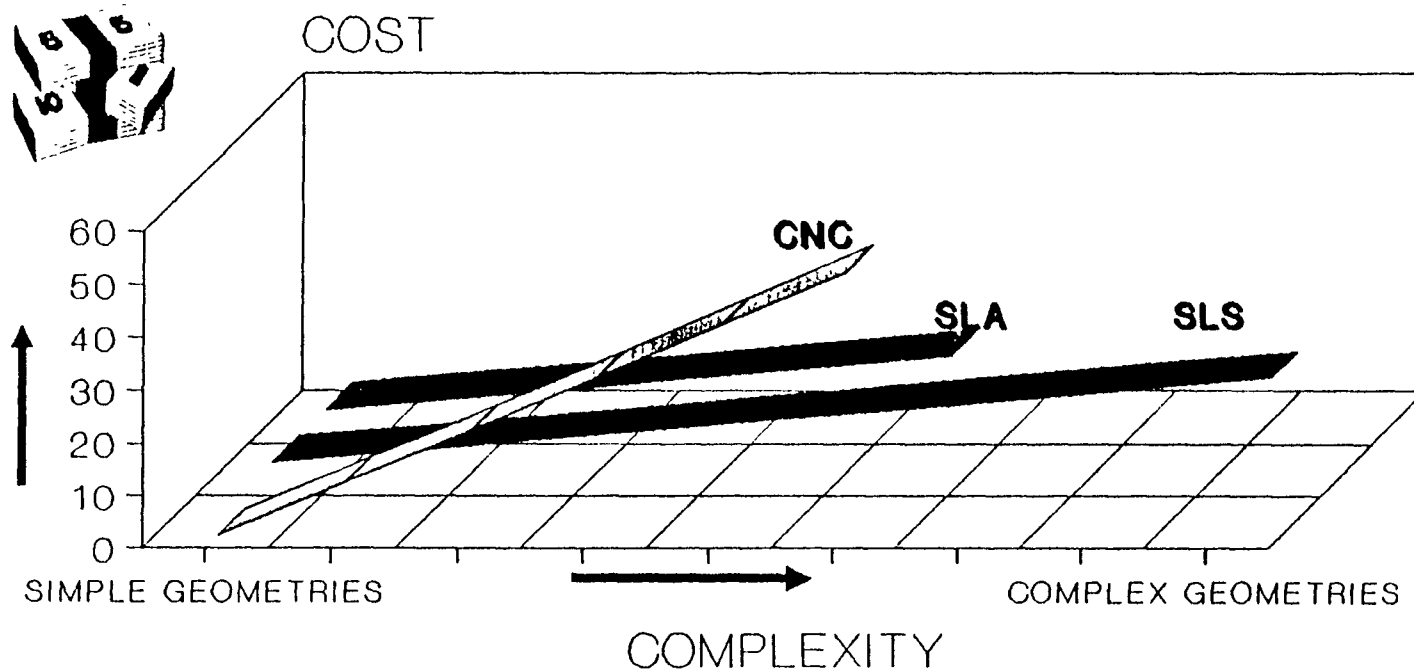
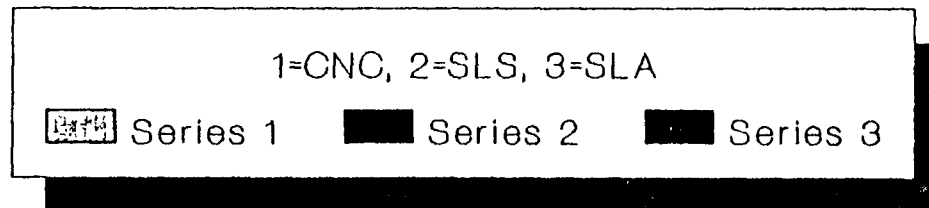


Figure: 7.6



increases very rapidly if the conventional machining operations being conducted on CNC. While on the other hand, the cost is increasing at a reasonable rate as the part is build using DTM systems. The results are based on data shown in table 7.4.

The two methods SLA and SLS are selected for the analysis because as complexity increases, after a certain limit SLA proves to be restricted due to liquid resin and support structure complication. But the SLS method could handle the job easily for the most of the complex part geometries.

7.3 Conclusions

The experiments performed were quite expensive, therefore are few in numbers, but they are still plentiful to steer us, to a number of clear conclusions.

Conclusion # 1

After comparing the sand casting methods and the SLA machine performance it was concluded that SLA is atleast 50 times better in terms of cost for making the same part.

Conclusion # 2

The result of the second experiment shows that the Desk Top Manufacturing system is 12 times faster than the conventional investment casting methods for building the

same prototype. It cuts a number of steps involved in the other investment casting methods.

Conclusion # 3

Observing many parts being made on the DTM system and the other machining systems gives the impression that the DTM is still, not suitable for large batch size as compared to the conventional machining techniques in terms of cost.

Conclusion # 4

The comparison for complexity of the part shows that due to the rapid increase in cost, as complexity increases, CNC machining technique is not feasible. On the other hand DTM system looks quite in control of the situation, as the complexity is not effecting the cost of building the part. Although most of the DTM systems can handle any complex geometry some have restrictions.

7.4 Final Recommendations

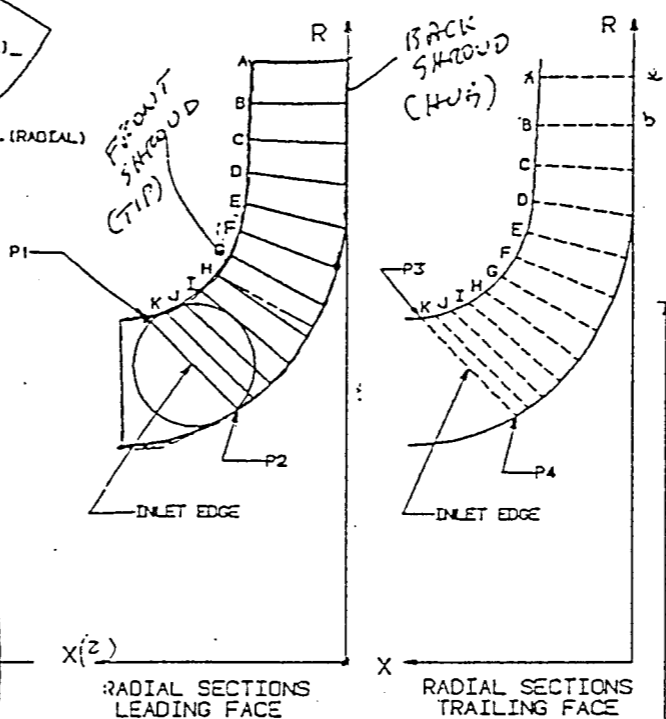
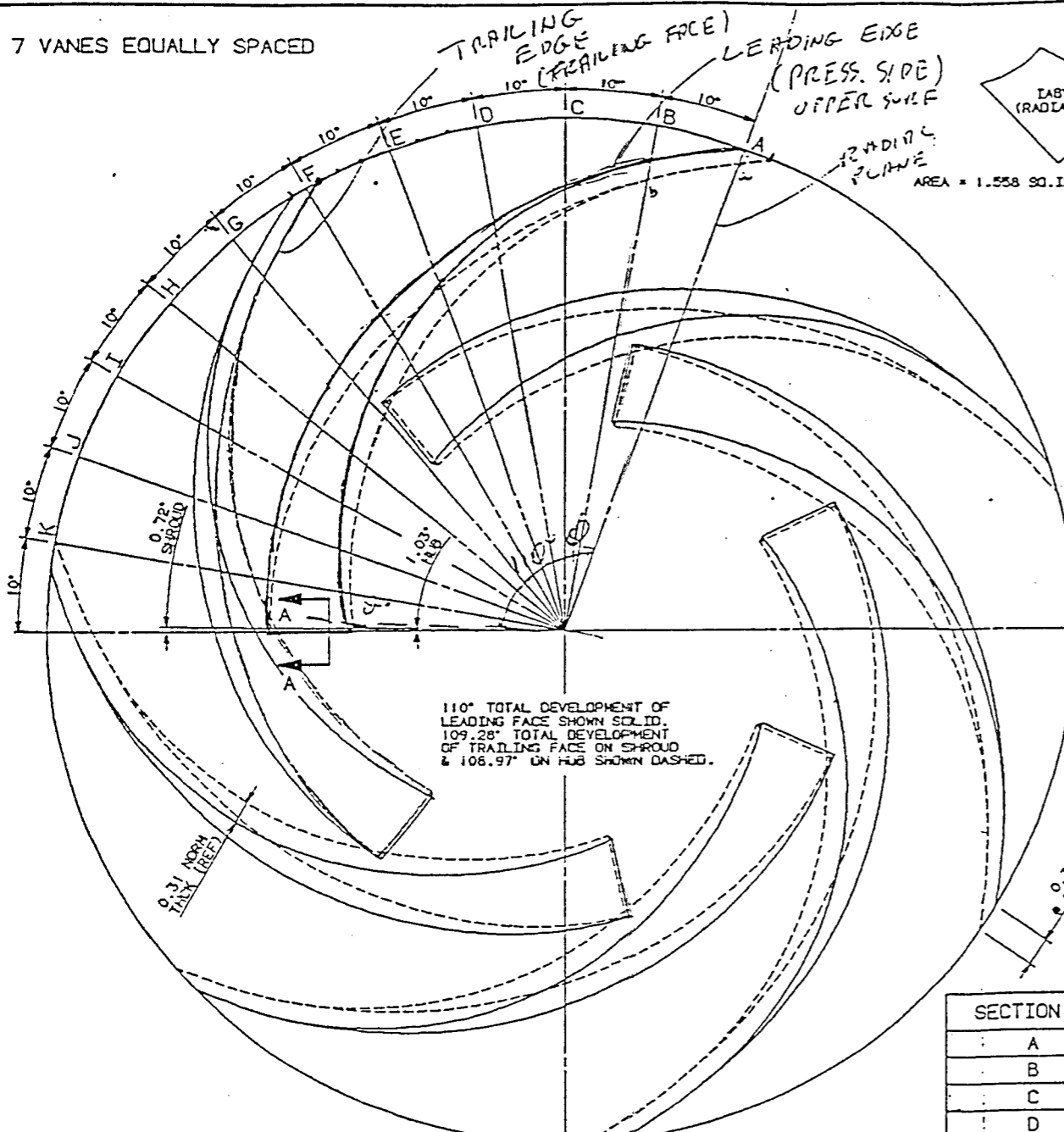
For the final remark after performing experiments and analyzing the results and conclusions over a wide band of performance parameters, It could be recommended that, the Desk Top Manufacturing systems are ideal when:

- a) The part is complex.
- b) The quantity of parts required is very little.
- c) The time factor is much important than the money.

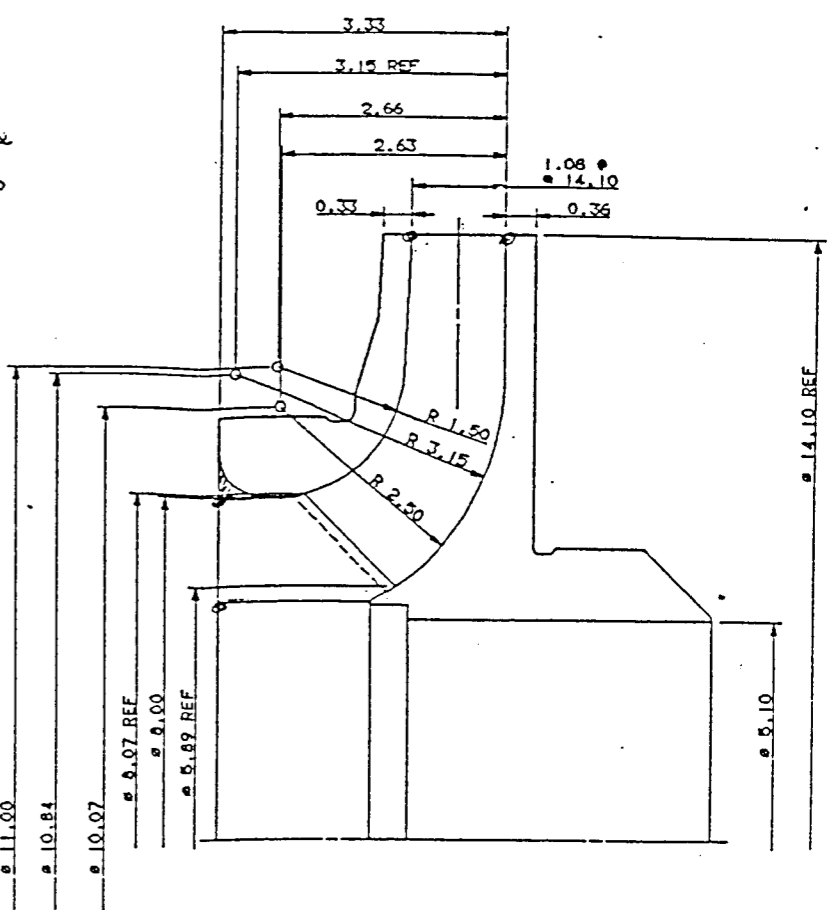
d) The accuracy can also be considered as a positive factor for selecting a DTM method over any conventional machining technique.

APPENDIX

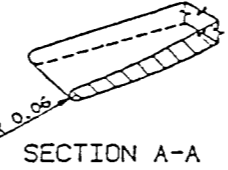
7 VANES EQUALLY SPACED



CO-ORDINATES OF INLET EDGE RADIAL SECTIONS ARE P1,P2(LEADING FACE) & P3,P4(TRAILING FACE).

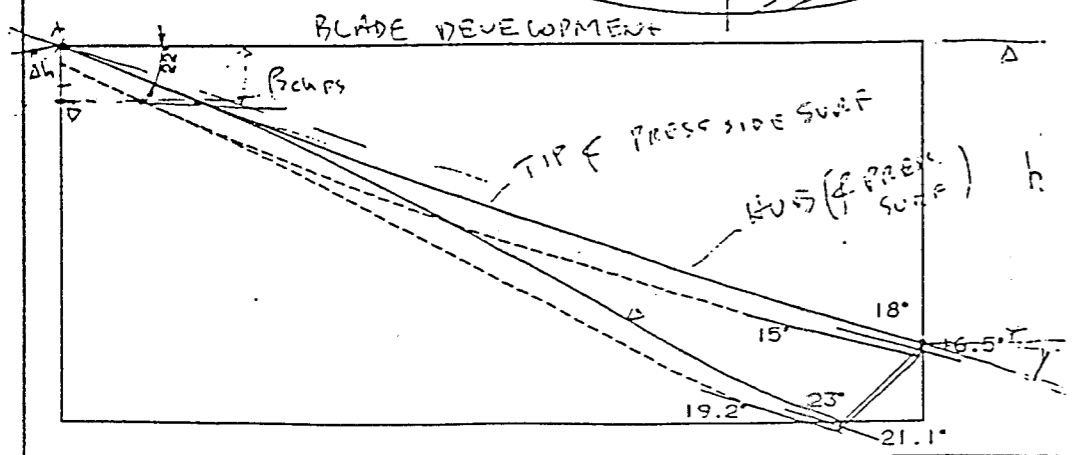


INVESTMENT CASTING



SECTION	LEADING FACE RADIAL SECTION COORDINATES				TRAILING FACE RADIAL SECTION COORDINATES			
	R	XZ	R	XZ	R	X	R	X
A	7.050	1.080	7.050	0.0	6.848	1.091	6.848	0.0
B	6.563	1.106	6.560	0.0	6.296	1.119	6.293	0.0
C	6.121	1.129	6.070	0.0	5.815	1.145	5.756	0.0
D	5.723	1.150	5.572	0.0	5.395	1.167	5.226	0.006
E	5.361	1.170	5.076	0.019	5.035	1.237	4.723	0.078
F	5.039	1.236	4.599	0.109	4.741	1.369	4.261	0.221
G	4.762	1.358	4.162	0.263	4.508	1.538	3.861	0.414
H	4.531	1.518	3.789	0.456	4.328	1.727	3.536	0.627
I	4.346	1.704	3.486	0.665	4.195	1.923	3.286	0.841
J	4.204	1.908	3.253	0.874	4.101	2.122	3.103	1.041
K	4.101	2.122	3.080	1.070	4.040	2.317	2.972	1.215
INLET EDGE	4.035	2.341	2.947	1.253	4.010	2.491	2.882	1.356

HYD. DATA
 Qo=3165 GPM $\phi=110^\circ$
 ql= 100 GPM De=8.00
 Qr=3265 GPM Dvs=8.07
 H=705 FT Dvh=5.89
 Ns=1467.96 Dm=6.94
 N=3570 $\phi=1.43$
 D2=14.10 BETA1s=18°
 B2=1.08 BETA1h=23°
 Z=7 Ae=29.83
 BETA2=22° IABV=10.90
 % EYE=36.56



BIBLIOGRAPHY

1. AINSWORTH JONES, SUSAN, PORTNOY, KRISTINE, "Making Prototypes Faster with Stereolithography," Chemical Week Vol: 141 Iss: 11, Sep 9, 1987 pp: 24-25.
2. ALEXANDER, MICHAEL, "DTM brings good things to 3-D life," Computerworld vol: 24 Iss: 33, August 1990, pp: 18.
3. ANONYMOUS, "Affordable Prototypes Are Made Without Tooling," Modern Plastics vol: 66, Iss: 3, March 1989, pp: 84-85
4. Autodesk, Inc. (1987). "AUTOCAD Users Reference." Sausalito, CA: Autodesk.
5. BAER, A., C. EASTMAN, and M. HENRION. (1979). "Geometric Modeling: A survey." Computer-Aided Design, 2, 5, pp: 253-272.
6. JOHNSTONE, BOB, "Prophet with honour," Far Eastern Economic Review, December 1990.
7. BESANT, C.B., C.W.K LUI, "Computer-aided Design and Manufacture," 3rd edn, Ellis Horwood, 1986.
8. CAD/CAM Inc. "Computer Aided Design Report," vol: 10, No.: 11, November 1990.
9. DEITZ, DANIEL, "Stereolithography automates prototyping," Mechanical Engineering vol: 112, No.: 2, February 1990, pp: 35-39.
10. DTM Inc., "DTM Bringing Competitive Advantage To product Design and Manufacturing," DTM Customer Support, March 1992.
11. FIDDORA, J.C., "Stereolithography models - the keystone for limited productions models," In Search of Excellence Annual Technical Conference, ANTEC - Conference Proceedings v 37. Publ by Soc of Plastics Engineers, Brookfield, CT, USA. pp: 2626-2628.
12. GETTELMAN, KEN M., "Stereolithography: Fast Model Making," Modern Machine Shop , Cincinnati, Ohio.
13. NUTT, KENT, "Linking CAD to Desktop Manufacturing," Computer-Aided Engineering, January 1991.

14. LINDSAY, KAREN F., "Rapid Prototyping Shapes Up as Low-Cost Modelling Alternative," Modern Plastics vol: 67 Iss: 8, August 1990, pp: 40-43.
15. LAWRY, MARK H., "I-DEAS Student Guide," Structural Dynamics Research Corporation, 2000 Eastman Dr., Milford, OHIO, 1991, chapter 3.
16. MURASKI, STEPHANIE J., "Make It in a Minute," Machine Design vol: 62 Iss: 3, February 1990, pp: 127-132
17. NEWMAN, W.M., AND R.F.SPROULL. "Principals for interactive computer graphics," 2nd edition. New York: McGraw-Hill.
18. STEVEN, ASHLEY, "Rapid Prototyping Systems," Mechanical Engineering, April 1991, pp: 34-43.
19. STOVER, R.(1984). "An Analysis of CAD/CAM Applications." Englewood Cliffs, N.J: Prentice Hall.
20. STRATASYS INC., "Fused Deposition modeling," Stratasys sales services, Minneapolis, April 1992.
21. CHANG, TEIN-CHIEN, RICHARD A. WYSK, HSU-PIN WANG, "Computer-Aided Manufacturing," Prentice-Hall, Englewood cliff, New Jersey, 1991, chapter 2.