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INSTITUTE OF NATURAL AND APPLIED SCIENCES

Ph. D. THESIS

Durmuş Ali BİRCAN

DEVELOPMENT OF A NURBS BASED ADAPTIVE SLICING PROCEDURE FOR FUSED DEPOSITION MODELING IN RAPID PROTOTYPING APPLICATIONS

DEPARTMENT OF MECHANICAL ENGINEERING

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DOKTORA TEZİ

MAKİNA MÜHENDİSLİĞİ ANABİLİM DALI

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ABSTRACT

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Introducing new products at ever increasing rates is important for remaining successful in a competitive global economy; decreasing product development cycle times and increasing product complexity require new ways to take in novel ideas. During the last decades, a new concept called Rapid Prototyping (RP), Layered Manufacturing (LM) has gained popularity in Turkey and worldwide especially in the area of product development, prototyping and tooling. The goal of Rapid Prototyping (RP) is to be able to quickly fabricate complex-shaped, three-dimensional parts directly from Computer Aided Design (CAD) models.
The aim of this study is to fabricate parts with minimum time and high surface quality using direct CAD based uniform and adaptive slicing algorithm in Fused Deposition Modelling (FDM) process. As an input, Non Uniform Rational B- Splines (NURBS) based model is used which is transformed from the Initial Graphics Exchange Specification (IGES) structure, which all commercially software packages can be saved as a IGES file easily. The user interface is created using Qt Designer and integrated with the CAD package of Unigraphics (UG). NURBS based CAD models were tested for uniform and adaptive slicing algorithms.

Keywords: rapid prototyping (RP), layered manufacturing (LM), direct slicing, NURBS, FDM

ÖZ

DOKTORA TEZİ

ERİTEREK MALZEME YIĞMA (FDM) HIZLI PROTOTİPLEME UYGULAMALARINDA NURBS TABANLI ADAPTİF DİLİMLEME PROSEDÜRÜ GELİŞTİRME

Durmuş Ali BİRCAN

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Teknolojideki ilerlemeye ve günümüz rekabet şartlarının artmasına paralel olarak, her geçen gün karmaşık parça, makine ve sistemlerin daha hızlı, kolay ve ucuz bir şekilde imalatına ihtiyaç duyulmaktadır. Bu durum çok farklı ve yeni imalat teknolojilerinin geliştirilmesine öncülük etmektedir. Yeni imalat teknolojilerinde varılan son noktalardan biri olan Hızlı Prototip Teknolojisi (HPT), son 10 yıldan günümüze kadar Dünya'da ve Türkiye'de hızla gelişme göstermiş, özellikle ürün geliştirme, prototip ve kalıp imalatı konularında önemli ilerlemelere sebep olmuştur. Hızlı prototip teknolojileri 3 boyutlu tasarım programı ile hazırlanmış modellerden fiziksel prototipler üretmeyi sağlar.

Bu çalışmanın amacı; FDM hızlı prototipleme teknojisinde Bilgisayar Destekli Tasarım (BDT) tabanlı uniform ve adaptif dilimleme algoritmaları kullanarak daha kısa sürede ve iyi yüzey kalitesinde parçalar üretmektir. Giriş olarak, bütün ticari BDT yazılımlarla kolayca transfer edilebilen IGES kullanılmış ve NURBS modellere çevrilmiştir. Qt Designer kullanılarak yazılım programıyla (UG) entegre arayüz oluşturulmuştur. Uniform ve adaptif dilimleme algoritmalarını test etmek için NURBS modeller kullanılmıştır.

Anahtar kelimeler: hızlı prototipleme (HP), tabakalı üretim, direkt dilimleme, NURBS, FDM

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Thanks and apologies to others whose I have overlooked here.

NOMENCLATURE

θ	: angle between center of the sphere and sampling point
d	: layer thickness
δ	: cusp height
ρ	: surface curvature
ε	: Slicing error or chordal error
X(u)	: Point in x direction on curve
Y(u)	: Point in y direction on curve
Z(u)	: Point in z direction on curve
N	: Number of segments for polynomials
CTYPE	: Spline Type for IGES definition
H	: Degree of continuity with respect to arc length
NDIM	: Number of dimensions, 2=planar, 3=nonplanar
T(1)	: First break point of piecewise polynomial
T(N+1)	: Last break point of piecewise polynomial
$A_X(1)$	
$B_X(1)$	: x coordinate polynomial
$C_X(1)$	
$A_y(1)$	
$B_y(1)$	: y coordinate polynomial
$C_y(1)$	
$A_z(1)$	
$B_z(1)$	: z coordinate polynomial
$C_z(1)$	
K	: Upper index of sum
M	: Degree of basis functions
u_o	: First value of knot
u_{n+p+1}	: Last value of knot
w_o	: First weight
w_N	: Last weight

P_0x

P_0y : First control point of x,y and z coordinates

P_0z

P_Nx

P_Ny : Last control point of x,y and z coordinates

P_Nz

u_{start} : Starting parameter value

u_{end} : Ending parameter value

n^x

n^y : Unit normal

n^z

m : Degree in the u direction

n : Degree in the v direction

B_i : Bernstein polynomials

$B_{i,n}(u)$

$B_{j,m}(v)$: basis functions

Pi, j : control points.

C^0 : parametric continuity

C^2 : Bezier curve

G^i : geometric continuity

cp : Control point

P : degrees in the u directions for B-Spline surface

q : degrees in the v directions for B-Spline surface

n : number of control points in the u directions for B-Spline surface

m : he number of control points in the v directions for B-Spline surface

α : angle between sides ρ and d

RP : Rapid Prototyping

LM : Layered Manufacturing

SLA : Stereo Lithography

SLS : Selective Laser Sintering

FDM : Fused Deposition Modeling

LOM : Laminated Object Modeling

3DP : Three Dimensional Printing

CAD : Computer Aided Design

CAM : Computer Aided Manufacturing

CNC : Computer Numerical Control

STL : Stereo Lithography file format

IGES : Initial Graphics Exchange Specification

STEP : The Standard for the Exchange of Product Model Data

ABS : Acrylonirite butadiene styrene

3D : Three-dimensional

CAE : Computer Aided Engineering

CIM : Computer Integrated Manufacturing

CLI : Common Layer Interface

CMM : Coordinate Measuring Machine

CT : Computed Tomography

FEA : Finite Element Analysis

LEAF : Layer Exchange ASCII Format

MRI : Magnetic Resonance Imaging

NC : Numerical Control

RE : Reverse Engineering

SFF : Solid Freeform Fabrication

SLC : Sliced Layer Contour

SLC : Stereo Lithography Contour

API : Application Program Interface

GUI : Graphic User Interface

UI : User Interface

HPGL : Hewlett-Packard Graphics Language

ASCII : American Standard Code for Information Interchange

B-rep : Boundary Representation

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1. INTRODUCTION

Nowadays product life cycles are gradually shortening throughout the industrial world. Furthermore a change is seen from high-volume production towards customer specific production of products in lower volumes. Moreover the products themselves are becoming more complex by adding more functionality.

In order to develop useful and profitable products, engineering has to deal with a wide variety of areas. These areas include: feature-based design, design for manufacturability, analysis, simulation, computational prototyping, virtual and physical prototyping, environmental aspects and ergonomics. Mechanical engineering is concerned with conceptualization and materialization of consumer products. A mechanical design engineer has skills to develop design concepts for new products, propose alternative designs and work out details with other members of the product development team from other disciplines. The design of these products needs to be carried out in a short time frame to survive in a competitive market. The above mentioned issues; the complexity of the products that, needs a deeper insight, the variety of products and the need to develop these products in a relatively shorter time result in a demand for effective design and decision support tools (Wohlers, 2001).

These tools must enable an earlier return on investment and a shorter time to market, therefore, a shorter time to money. It has been proved in practice that the use of both computer internal and physical models plays a crucial role in speeding up the product development process.

Since historical times it has often been the practice that either designers acting as model makers manufactured physical models or prototypes from initial sketches or professional model makers produced these objects on the basis of drawings. When the designer has the opportunity and the ability to work directly with materialized objects, it leads to a deeper and more comprehensive understanding of the design than it is possible with sketches and drawings. Nowadays however, physical models and/or prototypes are typically manufactured based on the design information embedded in computer internal product models (Abe

et all. 1999). The physical model can be made according to the dimensions and shape specified by the 3D geometric model. Therefore, there is no need for interpretation of drawings anymore. On the other hand, it raises the need for the complete and consistent specification of the design. Designers must take manufacturing constraints explicitly into account and adapt the Computer Aided Design (CAD) model accordingly.

The aim is to encounter and adapt the emerging manufacturing processes to generate physical models in order to support the product development process. These manufacturing technologies that generate physical models are often called Rapid Prototyping (RP), Layered Manufacturing (LM), Solid Freeform Fabrication (SFF), Automated Fabrication, Material Incress Manufcaturing, Rapid Manufacturing (RM), Desktop Manufacturing and Direct CAD Manufacturing. The key idea of this new rapid prototyping technology is based on decomposition of 3-D computer models into thin cross-sectional layers followed by physically forming the layers and stacking them up "layer by layer".

The goal of rapid prototyping is to be able to quickly fabricate complex-shaped three-dimensional parts directly from CAD models. LM methodologies have the following attributes:

- they can build arbitrarily complex 3D geometries,
- the process planning is automatic, based on a CAD model,
- they use a generic fabrication machine, i.e., do not require part-specific fixturing or tooling,
- they require minimal or no human intervention to operate.

The first commercially available layered manufacturing process appeared in 1987). Since then, a number of distinct technologies have been developed (Jacobs, 1992; Kochan, 1993; Jacobs 1995). Some of these technologies have already been brought to market as commercial products. Each of these processes and machines has its own specific merits. However, since these processes are relatively young and the technologies as such are not fully developed, the usage of these processes is not as straightforward as the basic principles suggest.

In LM, solid 3D CAD model of the object is first decomposed into cross-sectional layer representations in the process planner. The planner then generates trajectories for guiding material additive processes to physically build up these layers in an automated fabrication machine to form the object. Support layers are also simultaneously built up to fixture the object (Allen, 1994; Chalasani et all. 1995; McClurlin et all., 1998)

Each physical layer, which consists of the cross-section and a complementary shaped sacrificial layer, is then deposited and fused to the previous layer using one of several available deposition and fusion technologies. The support material has two roles: first; it holds the part analogous to a fixture in traditional fabrication techniques, second; it serves as a substrate upon which unconnected regions and overhanging features can be deposited. The unconnected regions require this support since they are not joined with the main body until subsequent layers are deposited. Another use of support material is to form blind cavities in the part.

All of the processes which will be reviewed require input from a 3D solid CAD model, usually as slices. The designer first uses a CAD package to design the product which wishes to manufacture. This model is then tessellated and exported as a Stereolithography (STL) file, which is the current industry standard for facetted models. If supports are necessary to brace any overhangs, proprietary software may add to the model. It is then sliced and the slices sent to the RP machine for the production of the final physical part. Figure 1.1. shows the RP building procedure.

1.1. RP Systems

In the late 1970s and early 1980s, there were several attempts to build three-dimensional objects using lasers (Beaman, 1997). In 1987, 3D Systems, Inc., USA introduced the first commercially available rapid prototyping system called “Stereolithography Apparatus (SLA)” (Jacobs, 1996).

Most of the RP processes can be classified into five categories based on their material building strategies (Beaman, 1997): Stereo Lithography (SLA), Selective

Laser Sintering (SLS), Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), and Three-Dimensional Printing (3DP). Stereo Lithography systems use light or laser to selectively solidify a photocurable material. Processes in the Selective Laser Sintering use laser energy to selectively sinter the powdered materials such as polymer, metal and ceramic powders. Laminated Object Manufacturing processes use plastic or paper sheets to build RP parts. Each sheet cut by laser is indexed over the previously cut patterns and bonded together using a heated roller. In Fused Deposition Modeling, a continuous filament of a thermoplastic polymer or wax is deposited through a heated nozzle layer-by-layer to build the RP parts. Some of the RP processes use the concept of Three-Dimensional Printing to create 3D solid parts. All of the processes mentioned here are based on the same idea: build the 3D complex objects with simple layers. Details of each rapid prototyping process are presented in Appendix A.

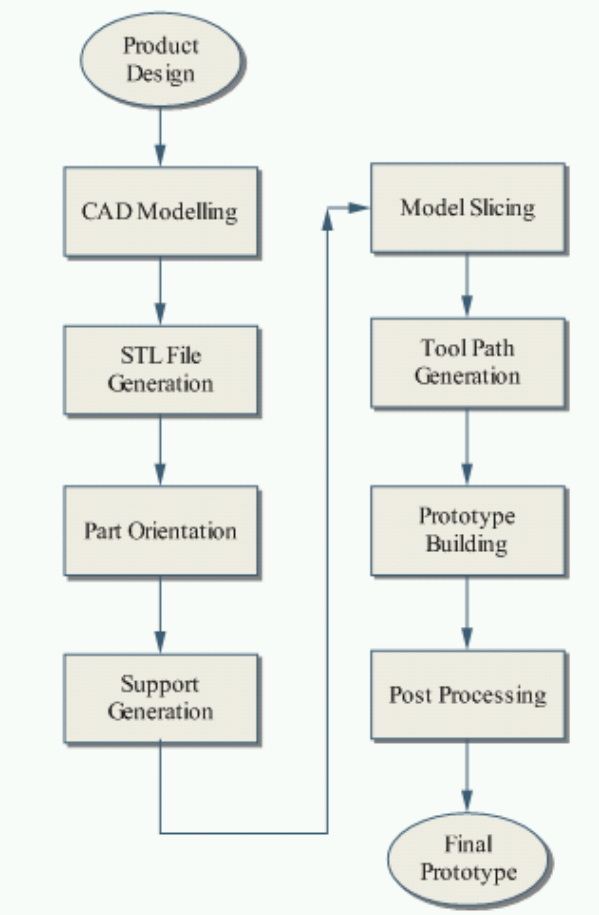


Figure 1.1. Overview of the rapid prototyping process

1.2. Advantages of Rapid Prototyping

Automated, tool-less, pattern-less RP systems can directly/effectively produce functional parts in limited production quantities. Parts produced in this way have an accuracy and surface finish inferior to those made by machining. The material and mechanical properties of these parts are not identical, but just close to those of the metals and plastics in common use today.

It is observed that over the last 25 years, products realized to the market place have increased in complexity in shape and form. This relative complexity index increased to about two in 1980 and close to three in the 1900's. However, the relative project completion times have not been drastically increased. With the use of Computer Aided design/Computer Aided Manufacturing (CAD/CAM) and Computer numerical Control (CNC) technologies, the project completion time could be reduced. Eventually, the RP systems can allow the project teams to further cut the completion time (Figure 1.2.).

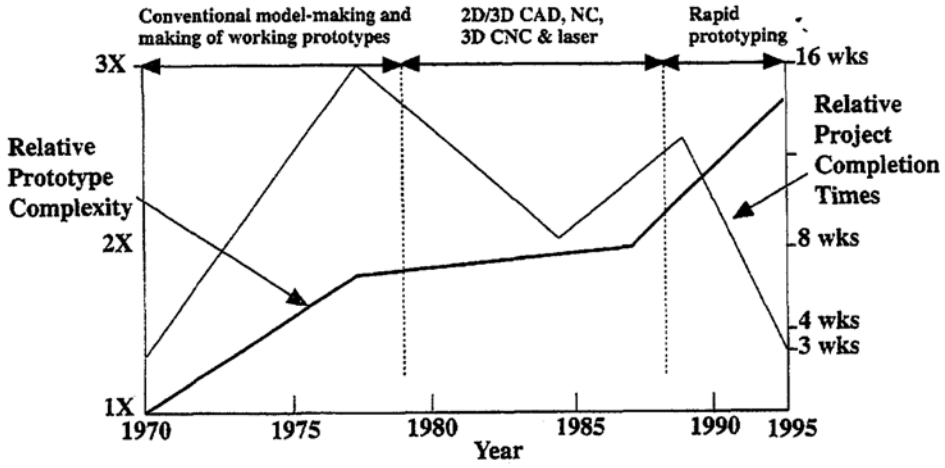


Figure 1.2. Project time and product complexity in 25-year time (Chua and Leong, 2001)

To the individual in the industry, the benefits can be varied and have different impacts. It depends on the role which they play in the competitive environment. Figure 1.3. shows how the RP technology affects to the entire spectrum of product

development and process realization. Depending on the size of production, savings in time and cost could range from 50 %up to 90 %.

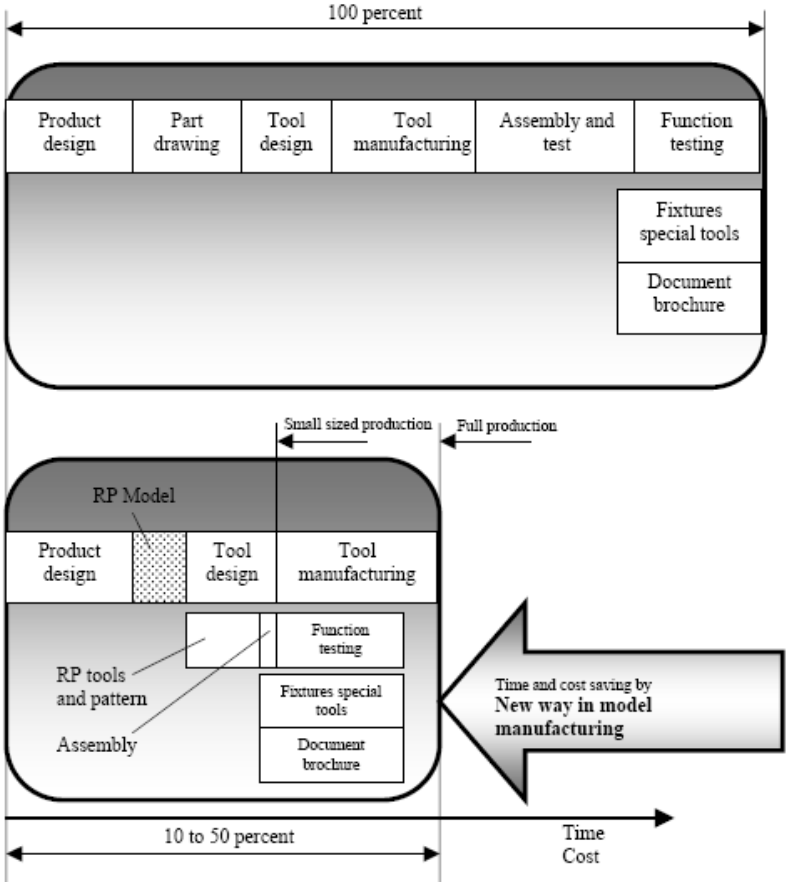


Figure 1.3. Result of the RP technology integration (Chua and Leong 2001)

1.3. Benefits of Rapid Prototyping

Rapid Prototyping has the following strategic benefits:

• **to reduce time to market:** Reduces the throughout product development time by eliminating or speeding up bottleneck processes in overall design cycle,

• t**o be responsiveness in manufacturing:** Modifies and customizes the products according to customers' requirements,

• **to support product development:** Ability of the generating models, prototypes quickly,

• **to decrease manufacturing unit costs:** Reduces the costs occurred by traditional manufacturing methods,
• **to increase labor productivity:** Eliminates time-consuming processes involved in making models and tooling,
• **to faster delivery to schedule:** Exploits time savings to manufacture products faster to meet due date promises,
• **to introduce new products:** Creates new models and new tooling very quickly,
• **to customize products:** Creates new models and tooling for each customer's customizations,
• **to change product specification:** Modifies and creates products and tooling according to customers' specifications,
• **to provide true and visual decision making mechanism:** Provides visual and just-in-time decision-making in product development time,
• **to cooperation between units:** Provides cooperation between design and manufacturing operations,
• **to create complex models:** Creates models regardless of the model shape complexity.

1.4. Position of the RP in Industry

The manufacturing technologies depend on the type of production and production volume (Figure 1.4.). The upper curve in the figure refers to the traditional manufacturing technologies while the lower two curves relates to computer-based manufacturing technologies. Since, the latter uses computer, they are more flexible and effective regardless of the geometric complexity of the parts being produced. They also involve significantly less tooling, so they are particularly effective for prototyping and low-to-medium batch production. Rapid technology belongs to this region and shows its uniqueness in addition to the NC, CNC and Computer Integrated Manufacturing (CIM).

The key benefits of the LM are mainly derived from its capability to rapidly fabricate physical models regardless of shape complexity. Using these technologies, the manufacturing cycle time for a typical rapid prototype part of virtually any complexity can be measured in hours instead of days, weeks or months depending on the method used. By decreasing development cycle times and increasing product complexity.

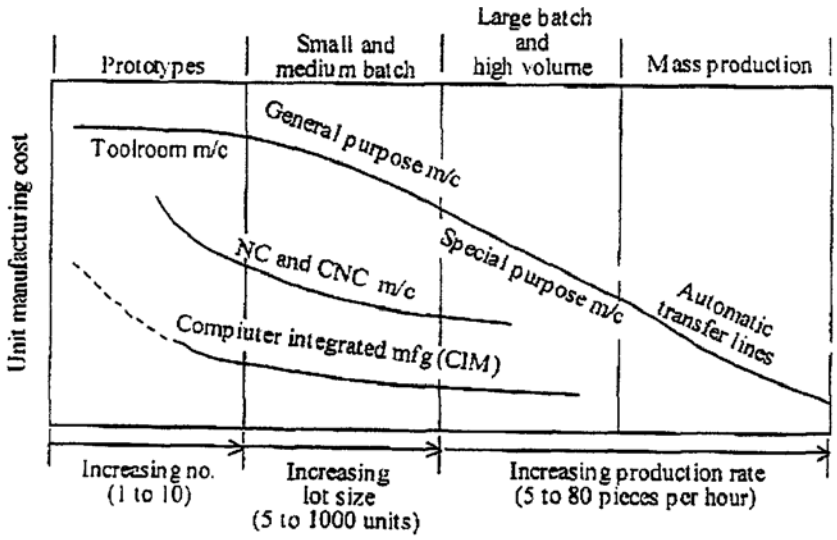


Figure 1.4. Impact of technology on unit manufacturing cost (Venuvinod, 2003)

1.5. Applications of RP

Areas of applications are closely related to the purposes of prototyping and consequently the materials used. The closer the LM materials to the traditional prototyping materials in physical and behavioral characteristics, the wider will be the range of applications. The key to increasing the applicability of RP technologies therefore lies in widening the range of materials.

In the early developments of LM systems, the emphasis of the tasks oriented towards the creation of "touch-and-feel" models to support design, which is creating 3D objects with little or without regard to their function and performance. It is the result that, it is limited by the materials available on LM

systems. However, as the initial costs of the machines are high, vendors are constantly in search for more areas of applications for functional evaluation, testing applications and eventually tooling. This not only calls for improvements in LM technologies in terms of processes to create stronger and more accurate parts, but also in terms of developing an even wider range of materials including metals and ceramic composites. Typical application areas are summarized in table 1.1. Details of application areas of rapid prototyping process are presented in Appendix B.

The major breakthrough of LM technologies in manufacturing has been their abilities in enhancing and improving product development while at the same time reducing the costs and time required to take the product from conception to market.

Table 1.1. Typical application areas of LM

Design	**Engineering, Analysis and Planning**	**Manufacturing and Tooling**

➢ CAD model verification
➢ Visualization of Objects
➢ Proof of concept
➢ Marketing and presentation model
	➢ Form and fit models
	➢ Flow analysis
	➢ Analysis of stress distribution
	➢ Pre-series parts
	➢ Diagnostic and pre-surgical operation planning
	➢ Design and fabrication of custom prosthesis and implants
		➢ Tooling mold parts
		  ➢ Direct soft tools
		  ➢ Indirect soft tools
		  ➢ Direct hard tools
		  ➢ Indirect hard tools
		➢ Casting
		  ➢ Sand casting
		  ➢ Investment casting
		  ➢ Evaporative pattern casting
		➢ Die casting
		➢ EDM electrodes
		➢ Master models

Industries		
➢ Aerospace ➢ Jewelry ➢ Consumer electronics	➢ Automotive ➢ Coin ➢ Home appliances	➢ Biomedical

1.6. Open Gaps in Rapid Prototyping

The first developments of RP technologies were mainly used for aesthetic purposes. But, the developments in recent years have led to many different applications. The quality of a prototype is no longer a "touch-and-feel" consideration. Accuracy becomes an important issue when the prototype is used for functional parts. Also, the efficiency of the whole process should be maximized to help decrease product development time and reduce life cycle cost. These two important factors: part accuracy and efficiency depend greatly on how the CAD model is represented and pre-processed for RP application.

Part accuracy: Part accuracy refers to the degree of deviation of the resultant part from the original CAD data. There are several sources of errors during the building of a part. These include:

- **Tessellation:** STL is the most widely used and the de facto standard in RP industry. It is an approximated triangulation model of a part with tolerance error specified by the user. The greater the tolerance, the less accurate the STL file is able to represent the part and so the part is built based on slicing this approximated triangulation data.
- **Staircase effects:** They are easily found on sloping planes or curved surfaces LM and affect the surface finish of the part. These are difficult to remove and have to be polished off during post-processing. Unlike the tessellation error, the extent of the staircase effects depends on the slicing thickness of the part.
- **Distortion and shrinkage:** These are related to the material properties and also the geometric features, such as the overhang surfaces.
- **Missing feature:** Some features are lost due to constant slicing thickness.
- **Overcure:** This refers to the additional layer formed below an overhang area due to the penetration of laser/nozzle through the previous layer.

Efficiency: Speed is one of the distinguishing features of an RP process when compared to conventional methods. The overall efficiency is limited by four elements:

- **CAD to RP translation:** This is the time spent in converting the CAD data to the instruction codes of the prototyping system. It involves STL file generation or similar procedure, pre-processing and geometric intersection in the slicing process. In building a complex part, the translation time is significant and hence efficient algorithms are devised to facilitate the process.
- **Communication between modeling and pre-processing:** The CAD modeling and pre processing steps are normally carried out independently. This may result in a lack of communication between the designer and the RP operator. For instance, designers generally have no means, at the design stage, of anticipating the shrinkage and exact outcome of the part during the RP process even if they have modeled it.
- **Building time:** This is mostly related to the height of the part in the working space of the machine. Generally the total number of build layers decreases with build height and a reduction in the number of layers will lead to a shorter build time.
- **Post-processing:** This stage involves the removal of the support structure, sand blasting, hand-finishing and coating of the prototype to provide an appropriate surface finish. Because most of the operations are performed manually, the danger of damaging a part is particularly high. Especially for a complicated part, it requires a high expenditure of time.

1.7. Research Objectives

The objective of this research is to develop a systematic procedure to improve the surface quality of a part built by a rapid prototyping process in FDM process. The main goal is to develop an approach to build a quality part as quickly and inexpensively as possible, using the FDM process.

Many rapid prototyping processes suffer from inaccuracy problems due to material shrinkage and distortion. Another common problem in rapid prototyping is poor surface quality. All rapid prototyping techniques have the same problem of the

stair stepping effect, which is a major cause of poor surface quality. These two problems; inaccuracy and poor surface quality, are current areas of research. As rapid prototyping progresses from a method of making physical models to a modern manufacturing technique, accuracy and surface quality will become more critical.

In addition to accuracy and surface quality, speed is also another major consideration in rapid prototyping. A rapid prototyping process is expected to produce the parts faster than traditional manual prototyping methods. In conclusion, accuracy, surface quality and building speed are among important research areas that should be considered for improvement of RP processes.

Accordingly, the main emphasis in this research is on improvement of part quality and reduction of building time in RP processes. As a matter of fact, there are always conflicts between the pursuit of quality and the pursuit of speed. Hence, tradeoffs are unavoidable when two conflicting objectives are desired. One of the goals of every manufacturing process is to make quality parts as quickly and inexpensively as possible. The part quality here is limited to only accuracy and surface quality aspects. As with other manufacturing processes, a main goal of rapid prototyping processes is to make acceptable parts with the lowest possible cost/time.

This research is focused on the improvements of the FDM process. Most of the research activities in rapid prototyping have been based upon the SLA process. Although all rapid prototyping techniques employ the same LM technology, their material, and processing technique are significantly different from one another. To understand the influences of parameters of a specific rapid prototyping technique on the quality of parts, a study must be performed using that technique.

Most of the inaccuracies exhibited on the parts are caused by machine inaccuracy, which is beyond the users control and is not considered in this research. Surface quality, on the other hand, is critical to all rapid prototyping processes, especially for the FDM process. Surface quality is significantly influenced by the machine parameters and part orientation used in the building process. Therefore, considerations must be made so that machine parameters and build orientation are selected appropriately. Conventionally, how well the machine parameters and build orientation are selected depends mostly on a user's experience.

In general, surface quality can be improved by using thinner layers. However, the use of thin layers requires that more layers be deposited, leading to a longer build time. Accordingly, some works have proposed the use of variable layer thickness. Variable thickness slicing, sometimes referred to as adaptive slicing, is a promising technique to speed up the building process while maintaining desirable quality. The use of variable thickness slicing, as opposed to uniform thickness slicing, can avoid unnecessarily thin layers that lead to additional building time.

There are many open-ended problems to be solved for precise and efficient part building using RP technologies. The main objective of this research, therefore, is to develop philosophy, strategies and algorithms for IGES based NURBS models in FDM process. In order to achieve the mentioned objectives, the following will be developed.

1. Detailed literature review has been prepared. The review highlights the latest work related to rapid prototyping, slicing algorithms, data transfer and optimization of process parameters for RP technologies.
2. Recognition of IGES files and converting Non-NURBS structures in the IGES files in to the NURBS curves and surfaces,
3. The creation of 3D slices to replace the commonly used 2D slices
4. Direct slicing from the CAD method to avoid inevitable errors which exist in STL file format is developed,
5. The adaptive slicing model to evaluate the performance of process parameters of RP system is developed,
6. C++ based OOP Graphical User Interface (GUI) for the part orientation, slicing, path planning and fabrication developed.

This work creates a CAD-integrated program structure for RP preprocessing. A user interface is created using Qt designer. The preprocessing operations of model orientation and slicing are developed in detail and verified on a set of test parts. A uniform and an adaptive slicing algorithm are created. Support planning, tool-path planning and machine file creation are process dependent and are not developed in detail in this work. Proposed structure of the thesis is shown in figure 1.5.

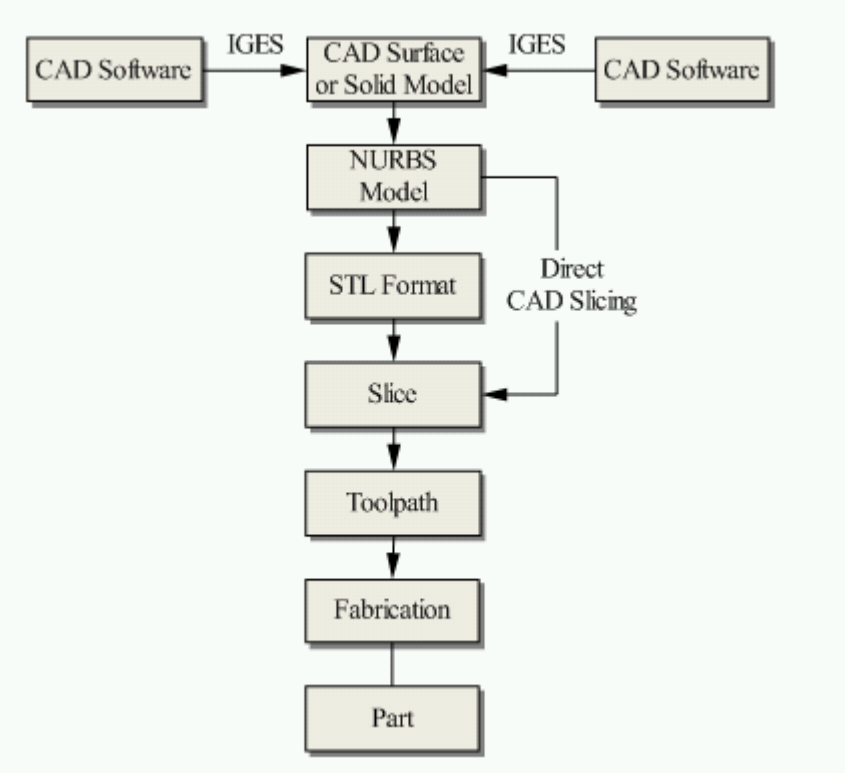


Figure 1.5. Proposed structure of the thesis

1.8. Thesis Organization

This thesis consists of four chapters, which are;

Introduction provides some general background on rapid prototyping. A summary discussion on each of the major rapid prototyping techniques is presented. In addition to the summary discussion of rapid prototyping systems, this chapter also summarizes application areas and benefits of RP. The objective of this research is stated at the end of this chapter.

Previous Studies reviews literature related to rapid prototyping. The literature covers topics including accuracy and surface quality improvement, methods to speed up the process, adaptive slicing, selection of optimal parameters and finally CAD and RP interfaces.

Material and Method provides some of the fundamentals used for developing this thesis. The chapter describes some underlying calculation methods

and algorithms for processing models. This section also proposes the methodology to achieve the objectives. Some file formats that are commonly used in rapid prototyping are discussed.

Result and Discussion illustrates a use of the system to build a part with lower slice numbers and time. The system is verified for its correctness. The implementation and verification of the direct and adaptive slicing algorithms are discussed for each sample part in this chapter.

Conclusion discusses the main issues arising from this research work and the results obtained from this study. The recommendations for future work are also presented.

2. PREVIOUS STUDIES

Recent researches on rapid prototyping, especially in FDM, mainly focus on the building process such as the part orientation, direct/adaptive slicing, RP interfaces. All these researches contributed to improved quality of parts and improved capability in producing complex models.

2.1. Process Planning in RP Processes

Process planning techniques in layered manufacturing have been widely discussed (Kulkarni et all., 2000). Process planning is performed to generate the tool paths and process parameters for an object that is to be built by a particular RP process (Marsan et all., 1996; Bircan, 2002). Although process planning software systems for RP are almost invariably optimized for a particular RP technique and cannot be used for alternative techniques, but four basic tasks can be found in RP techniques: build orientation determination, support structure generation, slicing, and path planning as shown in figure 2.1. The orientation of a part will affect the time needed to build the part, the surface quality and the need for support structures. Thus, before the part is sliced, an orientation must be determined based on a set of criteria important to the designer. With certain RP processes, layers that form overhangs or enclose voids must have a sacrificial support structure beneath them to support material as it is added. Such supports are built together with the part, then detached and discarded later. Some process planning systems design the supports after the part has been sliced, while others reverse this order. Finally, tool paths are generated and process parameters are set.

2.1.1. Part Orientation

The ability to evaluate and determine part building orientation for different rapid prototyping processes is important for building a satisfactory part within the limits of manufacturing time and building cost.

Part deposition orientation is an important factor of layered manufacturing as it effects build time, support structure, dimensional accuracy, surface finish and cost of the prototype. A number of layered manufacturing process specific parameters and constraints have to be considered while deciding the part deposition orientation.

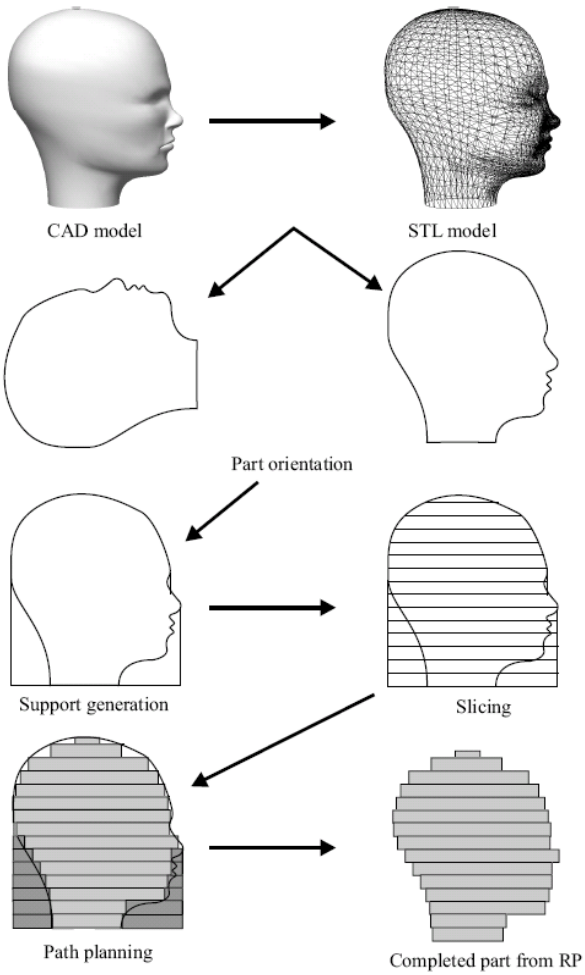


Figure 2.1. Process planning for RP (Koç, 2001)

Frank and Fadel (1994) suggested many factors get affected by the part deposition orientation. Some of these factors are surface quality; build time, amount of support structures, shrinkage, curling, distortion, roundness/flatness, resin flow, material cost and trapped volume etc. They considered the first three factors namely surface quality, build time and amount of support structures to obtain a better part deposition orientation. Surface quality was considered as the most important factor

because the functional requirements of the prototype have to be satisfied. They used minimization of stair stepping as a criterion to find the orientation that gives better surface quality. Stair steeping being the geometrical constraint of RP, it cannot be avoided but a user may be given a facility to orient the part in a direction that minimizes the stair stepping effect on a critical surface.

Frank and Fadel (1995) proposed an expert system that considers surface finish, build time and support generation. Only the quality of surface finish is considered as the rules determining a preferred orientation. Among many geometric features such as hole, surface of revolution, round surface, thin structure, plane and overhang, the user chooses two important geometric features of a part. The appropriate orientation is then selected from the surface finish and the support structure of these two features. Build time is estimated by roughly slicing the part.

Cheng and et al. (1995) proposed a multi-objective approach for determining the optimal part-building orientation. They considered different objectives such as part accuracy and building time. Objective functions have been developed based on known sources of errors affecting part accuracy and the requirements of good orientations during the building of a model for SLA process. The objective functions employ weights assigned to various surface types affecting part accuracy. The primary objective was to attain the specified accuracy achievable with the process. The secondary objective was to minimize the building time. The types of the surface defined can be identified directly from the CAD model. The reasonable weight determined in terms of the influences of the surface types on the accuracy. This algorithm can deal with type of the parts not only with flat and cylindrical surfaces, but also with complex surfaces. Since the number of possible orientations is finite and not likely to be very large for a given CAD model, it is possible to determine the optimal one computationally by using this enumerative approach.

Bablani and Bagchi (1995) developed a method to calculate the process planning error, process error and number of layers in different orientations achieved by rotating the given part about a user selected axis for the SLA process. As different orientations have different errors and number of layers requirements, the preferred orientation in their method is based on the user's selection.

Lan, Chou, Chen and Gemmill (1997) determined part deposition orientation based on the considerations of surface quality, build time or complexity of the support structures. Surface quality was evaluated either by maximizing the area of non-stepped surfaces or by minimizing the area of worst quality surfaces. The maximization of area of non-stepped surfaces was achieved by selecting a part deposition orientation that maximizes the total area of perpendicular and horizontal faces, which do not offer stair stepping. Candidate orientations are chosen by trying all the planes that are on the convex hull of the model as base planes and calculating the area of stepped surfaces, the build time and the number of supports. Build time was indirectly assessed by using the height of the part in the deposition direction. Support structure was minimized by minimizing number of supported points. Suitable orientation for one of the objectives at a time is determined from the list of pre-selected base planes.

Alexander, Allen and Dutta (1998) determined suitable part deposition orientation for better part accuracy and lower cost. Major source of part inaccuracy considered in their work was due to the stair stepping effect and is measured in terms of cusp height. The cusp height is calculated as the maximum normal distance between facet and the deposited part considering the edges of the slices to be rectangular. Slicing with constant layer thickness is considered. The weighted cusp height was defined as the multiplication of the area of the facet with the cusp height. Cusp height was weighed for the supported facets as it increases the inaccuracy. The average weighted cusp height was calculated by dividing the sum of weighted cusp height by the total area of facets. Surface accuracy was maximized by selecting an orientation that gives minimum average weighted cusp height among few pre-selected part deposition orientations. Alexander et al. proposed a generic cost model for RP part in which total cost of a model is sum of pre-build, build and post-processing costs. Build cost is due to manufacturing time and idle time. Difference in costs of model and support materials was taken into consideration. The post-processing cost is dependent on support removal cost and finishing cost. Specific cost models for FDM and SL were developed.

Hur and Lee (1998) developed an algorithm to calculate the staircase area. This quantified the process errors by the volume of materials to be removed or added to the part. It also calculated the layer thickness for the SLA system using the variable layer thickness. In addition, the total build time and the volume of the support structure were calculated. The optimal part orientation is determined based on the user's selections of primary criteria.

McClurkin and Rosen (1998) developed statistical models to predict build time, accuracy and surface finish of SL parts using response surface methodology. A face centered central composite experiment design was used to plan experiments. Layer thickness, hatch spacing, z-height and part volume were selected as variables. Layer thickness, hatch spacing and part deposition orientation were selected as design variables to be determined and build time, accuracy and surface finish as goals.

Pham, Dimov and Gault (1999) developed a system to orient CAD models for part deposition in stereo-lithography to obtain the best trade-off among build time, cost and accuracy. Their tool is a feature-based system that considers cost, build time, problematic features, optimally oriented features, over hanging areas and support volume for recommending a build direction. Their system has six modules, namely the orientation module, the support module, the timing module, the cost module, the problematic feature module and the display module. Candidate orientations are first chosen in orientation module based on considerations of critical surfaces, holes, cuts, shafts, protrusions, shells and axes. The unit vector in the build direction for each candidate part deposition orientation was stored. Each candidate orientation was then compared based on criteria. Their system sorts the candidate orientations for each criterion and a position score is assigned. User needs to specify a weight factor for each criterion as per the preference. The final score of each candidate orientation is then calculated by summing the multiplication of criterion weight and position score for individual criterion. The orientation that obtains maximum score is the most suitable part deposition orientation among the list of pre-selected orientations.

Xu, Loh and Wong (1997, 1999) discussed the selection of building direction for SLA, SLS, FDM and LOM. Main differences in the four processes are first examined with emphasis on the effects of differences with regard to the building

inaccuracy, surface finish, the manufacturing time and cost. An optimal orientation algorithm is demonstrated on a part considered for processing with each of the four RP processes. The influence of the process characteristics on the selection of appropriate orientation with different RP processes is illustrated in the example.

Masood, Rattanawong and Iovenitti (2000, 2001, and 2002) are developed a method for the determination of part orientation in rapid prototyping by considering the Volumetric Error (VE). The VE approach is especially relevant to the FDM process, where deposition of the material from a nozzle creates the VE more significantly compared to other RP processes. The methodology involves a primitive volume approach, which assumes that a complex part is to be constructed from a combination of basic primitive volumes. First, the VE in a number of primitive volumes such as cylinders, cubes, spheres and pyramids are considered. Then the VE in parts are determined. Mathematical equations for volumetric error are determined for orientations at different angles. Theoretical values of VE are compared with the experimentally determined values for each primitive and for example parts. Results are used to determine the optimal orientation on the basis of least amount of volumetric error.

West, Sambu and Rosen (2001) developed a process planning method for improving build performance, i.e. shorter build time, better accuracy and high surface finish in SLA. Part deposition orientation, layer thickness, sweep period, Z-height, fill over-cure and hatch over-cure are the six process variables were decided using the support structure and horizontal planes as the constraints. The part deposition orientation module developed by them works on evaluation of a set of the most feasible orientations based on the planar, conical and cylindrical surfaces on the part. The part is oriented in these pre-selected orientations and is sliced uniformly to trade-off among objectives satisfying the constraints of presence of support structure trapped volume, large horizontal planes and small or thin features.

Lin, Sun and Yan (2001) developed an optimization algorithm to define the fabricating orientation based on the minimum process error and proposed a mathematical model to predict the layered process error. Case studies have been

implemented to determine the preferred orientation for fabricating spherical objects, cube objects and objects with freeform shapes.

Masood, Rattanawong and Iovenitti (2003) and Rattanawong (2003) also presented research in determining the optimal orientation in the RP process using the VE approach. A generic algorithm has been developed to determine the best part orientation based on minimum VE in the part due to staircase effect. The part orientation system based on this algorithm is shown to work for a range of complex parts and a range of layer thicknesses. The system allows the part to be orientated in space by manipulation of rotation about any of the three axes individually or by rotation with a combination of two axes. The algorithm has been verified experimentally and mathematically by considering the VEs in primitive shapes and by actual parts built on the FDM RP system.

Thrimurthulu, Pandey and Reddy (2004) determined the optimum part deposition orientation using the genetic algorithm that considers surface roughness and build time for FDM. The surface roughness expression is obtained by measuring a part fabricated by FDM. It is difficult to apply the roughness expression to other RP processes, likewise, the build time expression cannot be applied to other processes. In addition, since the part is rotated only about one-axis, some candidate orientations could be missed. Therefore, the problem of determination of optimum part deposition orientation is formulated as a single objective optimization problem by adding two objectives, i.e. average part surface roughness and build time after multiplying by appropriate weights. The weights assigned to the two objectives represent the preference for them in determining the optimum part deposition orientation. Average part surface roughness is evaluated by slicing the tessellated CAD model of the part adaptively (Pandey, 2000). Build time is estimated indirectly by considering number of adaptive slices and weighing them with the ratio of supported area to the total surface area of the part.

Byun and Lee (2005, 2006) determined the optimal part orientation that improves the stair stepping effect. They also minimized the build time including the structure of the support in fabricating a completely freeform part. To avoid pre-selection operation, which is often troublesome and time-consuming, the genetic algorithm that

considers the fuzzy weight for surface roughness and builds time is used to determine the optimal orientation. To choose the best orientation, the genetic algorithm using user-specified fuzzy weights is employed. The validity of the study is demonstrated by three freeform models using SLA, SLS and FDM systems and compared with previous works.

Different published works for part deposition orientation determination are presented. Most of the researchers have considered part accuracy, build time, support structure and cost as a criterion to determine part deposition orientation. Few researchers determined part deposition orientation along with adaptive slicing and used cusp height as limiting parameter assuming build edge profiles as rectangular. Actual build edge consideration and its use in adaptive slicing and part deposition orientation has been recently done in which the optimal part deposition is investigated among all possible orientations.

2.1.2. Support Structures

Depending on the RP process used and its process planning software, support structures are added to the part either before or after slicing. For instance, the software supplied by 3D Systems for the SLA process requires input of a support structure in the form of an STL file. On the other hand, the software supplied by Stratasys for the FDM system will generate support structures by analyzing the 2D contours formed by slicing (Jacobs, 1992).

Part orientation and support structure determination are coupled problems, since some orientations of a part will require support structures.

Allen and Dutta (1994) calculated support structures to find optimal orientation with a minimal support structure. In their approach, they first tried to define candidate base planes by sampling points on the surface based on the reasoning of convex hull of the object. After obtaining candidate list of orientations of the object, support structure was calculated using Rays Structure for every orientation. Based on the calculation of the support structure, the best orientation was

chosen as the one which has minimal surface area of contact with the object and has a lower center of mass.

Allen and Dutta (1995) described a support structure design system, take a Brep solid as input, slice it and perform a computer simulation of the RP process. Three cases requiring support structures are detected: overhangs, floating objects arising during build that later become attached to the part and part instability during build. In the second and third cases, thin support columns are projected down from the object's surfaces to the base of the part. Overhangs are detected and appropriate supports generated on completion of the simulation.

Hur and Lee (1996) explained the procedures of generating support structures automatically. In their approach, it is assumed that the user could make necessary input, such as surface selection angle, maximum area for no support and overhang length for gusset support, etc. for support design. Using the input parameter values and criteria set based on the slope angle of face, instability and criterion for base support structure, they generated support structures. According to the area and the slenderness of the support facet group and geometric relation between adjacent faces, they determined the support type. Using the result of support generation, the optimal build orientation was determined based on the minimal sum of total projected supported area and total base area.

Allen and Dutta (1997) described an alternative approach to the support structure problem. They described how to modify a sliced hollow object to minimize the requirement for supports. For a given nominal wall thickness, the amount of overhang between adjacent layers can be determined. The user specifies the maximum amount of overhang that is allowed for a wall to be built without supports. If the amount of overhang between two slices exceeds this maximum allowed amount, the walls of the lower slice are thickened so that the overhang constraint is met. From the informational point of view, requirements for support structures are determined from the geometry of the part, as described by a 3D boundary model or 2D slices and the maximum draft angle the selected RP process can build without supports. Support structure software generates boundary models of the required supports or adds support contours to a slice representation of the object.

2.1.3. Slicing

All current commercial RP systems require that the geometry to be fabricated be described in the .STL file format. Once in this format, the geometry is sliced to obtain the horizontal cross-sections. These cross-sections are then used to generate the NC tool paths required by the fabricator (Fadel and Kirschman, 1996).

The .STL file format consists of an unordered list of triangular facets that approximate the actual surfaces of an original CAD model. It is a boundary representation of 3D geometry. The .STL file format has become the de facto industry standard for describing CAD models to RP processes for reason of its extremely simplistic format for describing CAD models minimizes the cost of providing one-way translation. As a result, most CAD vendors have developed software that is capable of translating data to this format. However, the .STL file format contains minimal topological information. Specifically, it contains a list of possibly unconnected triangular facets. Hence, there is no guarantee that a .STL model is closed and properly oriented. A model that is not closed and properly oriented cannot be fabricated because it does not describe a rigid solid. Therefore, it must first be repaired before it can be sliced (Chua et all., 2003; Gibson, 2002, Kamrani, 2006).

The lack of topological information in the .STL file format is also a source of unnecessarily large files containing redundant and possibly inconsistent data. In the .STL file format, each facet is represented by three vertices whose coordinates are explicitly described. This causes considerable redundancy since each vertex is described once each time it is used, which is at a minimum three times and often ten times or more. The .STL format also explicitly describes the surface normal for each facet, in addition to defining it implicitly by the order of the facet's vertices. These duplications are sources of inflated file sizes and possible inconsistencies.

Yan and Gu (1994) presented a review of the main error sources of RP. The small triangle collapse in data preparation is identified as one of the error sources. To overcome this problem, the authors propose an approach to data preparation for rapid prototyping based on the Constructive Solid Geometry (CSG) modeling and the ray

tracing algorithm. This approach can eliminate the errors due to the small triangle collapse. It also improves the accuracy of the data preparation and reduces process lead time and the size of data files.

Dolenc and Makela (1994) reported an overview of current data exchange formats used in RP and explore their role in connection with data preparation. The paper explains the interplay between the data exchange format, application programs and final functionality that these programs should deliver to a user of rapid prototyping technology.

Fadel and Kirschman (1996) presented a summary of CAD to RP file formats and explained the accuracy issues associated with each representation. The paper provides overview of rapid prototyping file formats including HPGL, STL (ASCII and Binary), SLC, SLI, IGES, STEP, CLI, CFL and RPI. The accuracy issues discussed in the paper include tessellation, flipped normals, and more than two triangles per edge, closure errors and truncation error. The study also provides a list of software tools available to facilitate the bridging between CAD and RP, along with their capabilities and approximate dates of release.

In addition to CAD models, some sources of input, such as data from coordinate measurement machines, can be used to build the prototypes, as well. Chen et al, (1997) propose an integrated Reverse Engineering (RE) approach to generating free-form surfaces. The procedure creates CAD-compatible free-form surface models with a coordinate measurement machine and a touch trigger probe. The approach integrates data digitization and surface modeling to obtain an efficient and accurate digitization process with a collision-free exploration path and to reconstruct least-squares bi-cubic B-spline surface models for rapid product prototyping. This approach significantly reduces the product development lead-time and obtains a surface model with controlled digitizing accuracy.

Two common types of surface defect are normally encountered in parts built on a RP system. The first type, chordal error, is caused by the STL format representation of the CAD model of the part, which consists of a web of triangles representing the surface. Thus, all curvilinear surfaces must be approximated as a series of linear segments leading to a non-smooth surface of a part. This can be

reduced to some extent by increasing the tessellation of triangles, but this may produce a very large STL file leading to computation problems.

The other type, staircase error as shown in figure 2.2., is caused by the layer-by-layer nature of the rapid prototyping building process. Inclined and curved surfaces show staircase effects more predominantly than other surfaces. The orientation can have a significant effect on the quality of various surfaces of the part. The staircase effect cannot be eliminated on a RP part completely. Due to the presence of stepped edges, slices may be outside or inside the CAD model as shown in figure 2.3. However, the effect can be reduced by decreasing the layer thickness and by orienting the part so that the effect of overall staircase error is greatly reduced.

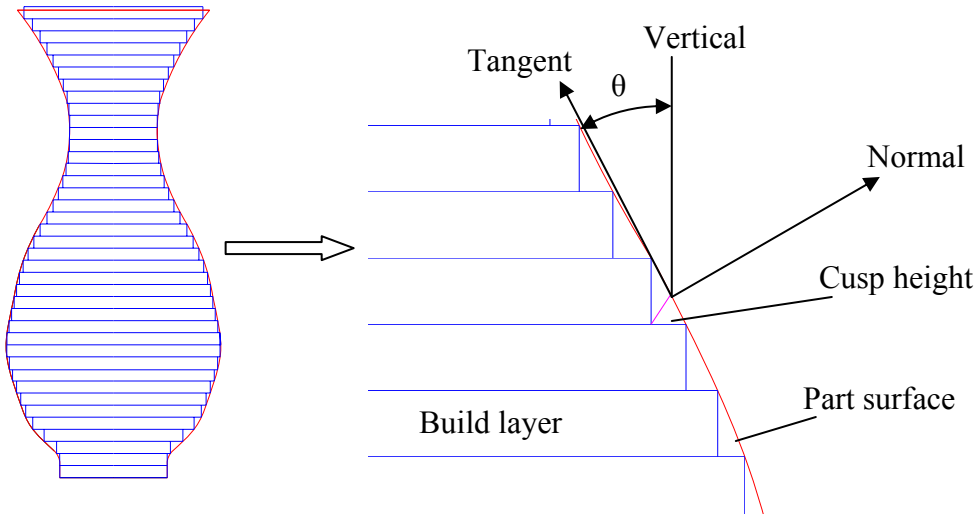


Figure 2.2. Staircase effect in RP parts

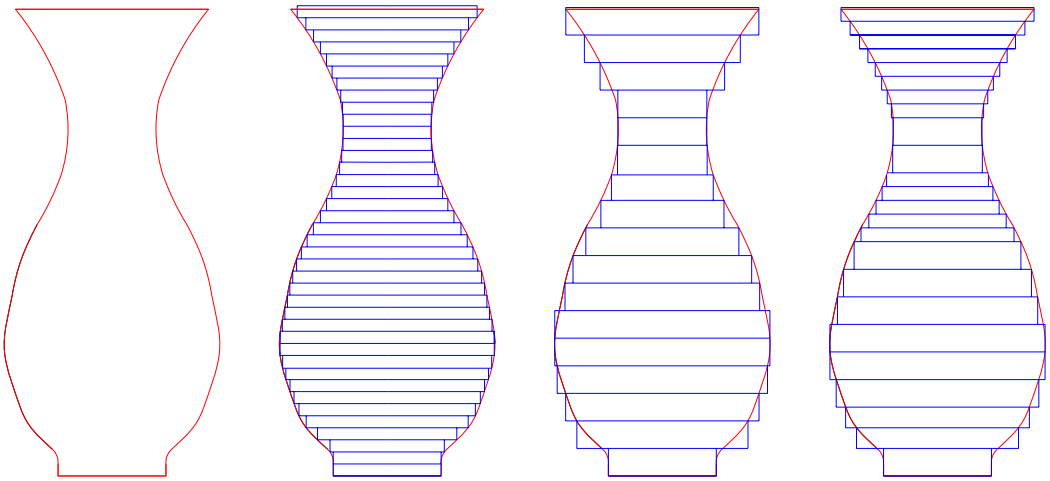


Figure 2.3. Deposition inaccuracies in RP parts

The problems of staircase and containment are of major concern as they affect the final quality of the prototype. Refinement of layers improves the surface finish of the part, but it increases the build time. The cost of the prototype is directly governed by the build time. This contradiction between build time and surface finish led to the development of different slicing algorithms. Initially, uniform layer thickness was used to slice the CAD models. Later adaptive slicing procedures which use slices of variable thickness instead of constant thickness were developed and their thickness is governed by the part geometry and RP machine specifications.

2.1.3.1. Slicing of Tessellated CAD Model

The most significant development in RP technology, in terms of improved part accuracy, has been adaptive slicing. The basic principle of adaptive slicing is to evaluate local surface geometries to determine the maximum build layer thickness that can be used while maintaining a user-defined surface tolerance, usually measured by the cusp height. The cusp height represents the maximum deviation of the part surface from the true surface. As shown in figure 2, it is measured in the direction normal to the true surface. The layer thicknesses are usually distinct values bound by which are pre-determined by the user and which are limited by the

fabrication capabilities of the specific RP process. Existing methods typically incorporate mathematical expressions that predict the cusp height at discrete locations along a given slice.

Dolenc and Makela (1994) proposed an adaptive slicing method for RP. The CAD model was first sliced uniformly into slabs of thickness equal to the maximum available thickness. Each slab is then resliced uniformly as needed to maintain the desired surface accuracy. This approach improved on by determining the adaptive refinement through interpolation rather than extrapolation and it is well suited for execution in a parallel processing computer. The method has been implemented and tested with .STL CAD models on a Stratasys FDM 1600 RP system, where typical measured build times were reduced by approximately 50 per cent without reducing overall surface accuracy.

Suh and Wozny (1994) estimated the error in the tessellated CAD model by maintaining the cusp height as the maximum deviation between the CAD model and the tessellated model along the normal to the triangle of the tessellated model. They determined the layer thickness using a set of sample points from the previous layer contour. By approximating the model surface curvature ρ and using the cusp height tolerance δ, the layer thickness d is calculated.

On upward facing surfaces

$$d = -\rho \sin\theta + \sqrt{\rho^2 \cos^2\theta - 2\rho\delta - \delta^2} \tag{2.1}$$

$$d = \begin{cases} \rho\cos\theta - \sqrt{\rho^2 \cos^2\theta - 2\rho\delta - \delta^2} & (\rho^2 \cos^2\theta - 2\rho\delta - \delta^2) > 0 \\ \rho\cos\theta & \textit{otherwise} \end{cases} \tag{2.2}$$

where

d : layer thickness at the considered sampling point;

δ : cusp height tolerance;

ρ : surface curvature at the considered sampling point;

θ : angle between center of the sphere and sampling point.

The optimal layer thickness is the minimum calculated value in the set of sample points of the layer contour.

Kulkarni and Dutta (1995, 1996a, 1996b, 1996c) developed a procedure for the adaptive slicing of a parametrizable algebraic surface using cusp height criterion. The acceptable cusp height is specified by the user. The slicing technique computes slices of varying thickness based on the bounding surface geometry to satisfy user-defined cusp height. The geometry is limited to parameterizable algebraic surface so that the exact expression for the surface curvature in the vertical direction can be extracted.

Sabourin, Houser and Bohn (1996) developed approach to adaptive slicing that it is first subdivided the model space into thick, uniform, horizontal slabs of thickness equal to the maximum acceptable layer thickness. These slabs are then subdivided individually as needed to satisfy the maximum cusp height. This method accommodated parallelism in that the slabs, being of uniform thickness and at predictable locations, are easily identified and distributed among parallel sub-processes for final slice thickness determinations and subsequent slicing. It also accommodates the use of interpolation in place of extrapolation for optimal slice thickness determination. Specifically, a slab can be examined both from its bottom slice looking upward and from its top slice looking downward. Experiments showed that parts fabricated with adaptive layer thicknesses on an FDM 1600 RP system maintain an overall surface accuracy equivalent to a uniform 0.13mm layer thickness, but with an approximate 50 per cent reduction in fabrication time. Additional savings in fabrication time can be realized if the thicker layers are fabricated with their wider default material deposition bead width than the experimental uniform thin bead width.

Tyberg and Bohn (1998a, 1998b, 1999) presented an approach to adaptive slicing that first identified the individual parts and features that comprise each layer in a given build and then slices each independently of one another. This technique improves upon existing adaptive slicing algorithms by eliminating most of the slices that do not effectively enhance the overall part surface quality. Conventional adaptive slicing methods produce unnecessary layers that contribute to increased fabrication times without improving the overall quality of the part surfaces. Unnecessary layers result from fabricating all of the parts and features within the

build volume at a given height using a single build layer thickness. Each thickness is commonly derived from the one part or feature existing at that height whose surface geometry requires the thinnest layer to meet a tolerance criterion. This approach has been implemented on an FDM 1600 rapid prototyping system, and has demonstrated a 17-37 per cent reduction in fabrication times compared to that of conventional adaptive slicing methods.

Sabourin, Houser and Bohn, (1997) developed slicing method to fast layered manufacturing and its integration with commercial rapid prototyping software for FDM. In particular, sample parts have been fabricated in significantly less time without sacrificing surface quality. This approach improved previously studied work by identifying the interior regions of a part and depositing the build material in these regions at a significantly increased rate relative to that used in the exterior regions of the part. Specifically, this approach alternates between first depositing several thin layers of build material to fabricate a vertical section of the exterior regions and then backfilling the interior regions at a significantly higher rate. Experiments have been showed that for sample dense parts the interior region fill rate can be increased by a factor of five or more over conventional material deposition rates to yield an overall 50-80 per cent reduction in build time without affecting the surface quality or part integrity. Additional saving in fabrication time can also be realized by continuing to increase the interior region fill rate and by adding lattice and other voids to the interior region.

Tata, Fadel, Bagchi and Aziz (1996, 1998) presented an algorithm that can vary the layer thickness in relation to local geometry. This algorithm based on three fundamental concepts: choice of criterion for accommodating complexities of surfaces, recognition of key characteristics and features of the object and development of a grouping methodology for facets used to represent the object. Four criteria, cusp height, maximum deviation, chord length and volumetric error per unit length are identified and the layer thickness is adjusted such that one of the four is met. Next, key characteristics of the object, such as horizontal and vertical surfaces, pointed edges and ends, are identified based on the local changes in surface complexity and slice based feature recognition is introduced to identify the nature of

a feature, protrusion or depression, by studying the slice data. Finally, the concept of grouping of the facets based on their vertex coordinates is developed to minimize the number of searches for possible intersection of the facets with a slice plane. The slicing algorithm is interfaced with adaptive laminated machining and the stereolithography process through a CNC post processor and a hatching algorithm respectively.

Cormier, Unnanon and Sanni (2000) proposed an interactive procedure for gathering cusp height requirements for the different faces of the part. The procedure started by applying an edge finding algorithm for the STL file and grouping facets together according to the face that each facet belongs to. The procedure then utilized functions from the OpenGL graphics library to render the faceted model and to highlight faces one at a time. For each highlighted face, the user is prompted to input the maximum allowable cusp height or to accept a default value. The procedure can be easily implemented as a preprocessor to any adaptive slicing system.

Pandey, Reddy and Dhande (2003a, 2003b, 2007) proposed a slicing algorithm based on the realistic edge profile of FDM. In this work, Ra value is used as a user specified parameter instead of the cusp height. The major advantage of using Ra value in the place of cusp height is that Ra value is most commonly used in integrated design and manufacturing. In real practice, the edge profiles of a layer manufactured part using FDM is found to be parabolic. A stochastic model is developed for surface roughness prediction. The Ra value of the part is found to be dependent on the layer thickness and build orientation. They studied the effect of radius of curvature on Ra and concluded by using a neural network model that the radius of curvature effect on surface roughness can be thought of independent as it varies within 5 percent over a wide range of curvature values. The layer thickness for a maximum specified Ra value on the part surface is calculated. The procedure is implemented using C and OpenGL. Average part surface quality in terms of standard Ra value is also predicted in the developed algorithm.

2.1.3.2. Direct CAD Model Slicing

Direct CAD model slicing originated from the desire to provide RP fabricators with a CAD model description that was more accurate than that provided by the .STL file format. A model description in the .STL file format can only approximate the curved surfaces of a CAD model. Furthermore, the cross sections resulting from slicing tessellated models are comprised of polygonal contours that can only approximate the true cross-sections of higher order surfaces such as spheres or Non-Uniform Rational B-splines (NURBS). In addition, the translation of CAD models to the .STL file format often produces errors such as missing and intersecting facets and repairing these models is an expensive and imperfect task. One approach to resolve these issues is to slice the CAD model directly.

Even though tessellated CAD data format has number of advantages still it has several limitations. The exported .STL file is sometimes larger than the original CAD file because it has high degree of redundancy since each triangle is individually recorded and shared ordinates are duplicated. Tessellated CAD data files generally carry defects like gaps, overlaps, degenerate facets etc. hence, repair software is needed. Sometimes it is not possible to get back the original CAD model through the .STL interface successfully. Slicing of large .STL file may take long time. The slicing error (real error) is quite high as compared to chordal error due to tessellation as shown in figure 2.4.

Planar closed curves result, when a horizontal plane is intersected with CAD model during slicing. These contours may either be produced by a three-dimensional CAD model, RE technique, coordinate measurement machine or by CT. Direct slicing may prove most useful for RP users, who produce large axisymmetric or spherical geometries because they suffer the disadvantages of large tessellated files. The direct slicing has potential in terms of reduced file size, greater model accuracy, reduced RP post processing time and elimination of repair software. However, there are some limitations with direct slicing. The implementation of program for adding support structure is not easy. The ability to orient the model is minimum, as CAD model is stored in the form of analytical surfaces or mathematical definitions instead

of coordinates of points as in the case of tessellated models. Therefore, more designer knowledge is needed, as software support is not readily available.

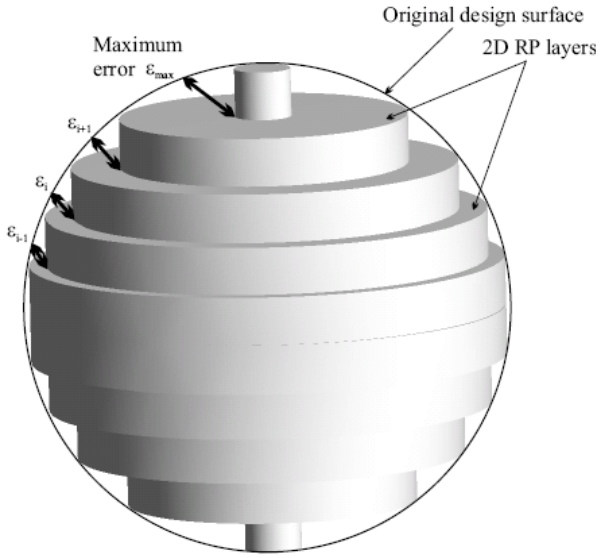


Figure 2.4. Slicing error or chordal error (Koç, 2001)

Direct slicing of CAD models with uniform slice thickness was implemented first using parasolid CAD software and user defined routines in C programming language by Jamieson and Hacker (1995). Parts were modeled using boundary representation method. These models had non-manifold problem, which was avoided by giving tolerance to the sectioning plane in the positive or negative *Z*-direction. The slicing algorithm started with the finding of the highest and lowest points of a part. The slicing direction is chosen as the *Z*-direction. The slicing of the part is achieved by consecutively calling the function for one slice and then putting the tags of the slice together in an assembly. An optional adaptive slicing approach is provided which was based on the limited area deviation. The thickness of a layer always remains between the maximum and minimum fabrication thickness available in the RP system.

Zhao and Laperriere (2000) also carried out the adaptive slicing of solid models using the concept of limited area deviation, but implemented the procedure using AutoCAD Run Time Extension (ARX) and C++.

Kulkarni and Dutta (1996) was studied the effect of containment and staircase on the final product accuracy and surface quality. Vertical normal curvature and normal vector at any point of a CAD model is computed. Two approaches used for finding the slice thickness. Maximum curvature and minimum layer thickness approach. The minimum layer thickness approach is reported to yield better results compared to maximum curvature approach. The procedure of slicing was carried out in two steps. In the first step, the model was divided into distinct sectors so that sharp features were not missed as the circular approximation of a vertex may yield erroneous results. In the second step, these separated sectors were sliced based on the specified cusp height. Adaptive slicing of an arbitrary object, which has many bounding surfaces, is carried out by extracting their geometrical definition. These surfaces are then converted into parametric splined surfaces and then slicing is performed.

Hope, Jacobs and Roth (1997a, 1997b) used sloping build edges instead of rectangular edges for the better approximation of surface of the part. The main advantage achieved is improved surface finish and decreased build time as thick layers can be used. In this work, multiple B-spline surfaces from IGES format were used to define a part. They sliced the model by tracing surface contours, and computing the cutting direction at a number of points as specified by the user. These points and corresponding cutting vectors are used to generate CNC code to machine the slices. Hope also developed a system named “TruSurf” which utilizes the layers with sloping surfaces and constant layer thickness.

Mani, Kulkarni and Dutta, (1999) was implemented flexibility of imposing different cusp heights on the different surfaces of the model. Difference between traditional adaptive slicing and region-based adaptive slicing is shown in figure 2.5.

They described a new slicing strategy, Region-Based Adaptive Slicing (RAS) where each surface of the CAD model is adaptively sliced based on its geometry and its surface finish requirement. Surfaces that are important, termed as critical surfaces, can have different surface finish requirements. These critical surfaces are adaptively sliced, while the interior of the part and other non-critical surfaces are sliced with the maximum possible layer thickness to reduce the build time. In this model, the critical

surface is the curved surface. Since the vertical block B is not a critical surface, in RAS as well as in traditional adaptive slicing, it is sliced at maximum thickness.

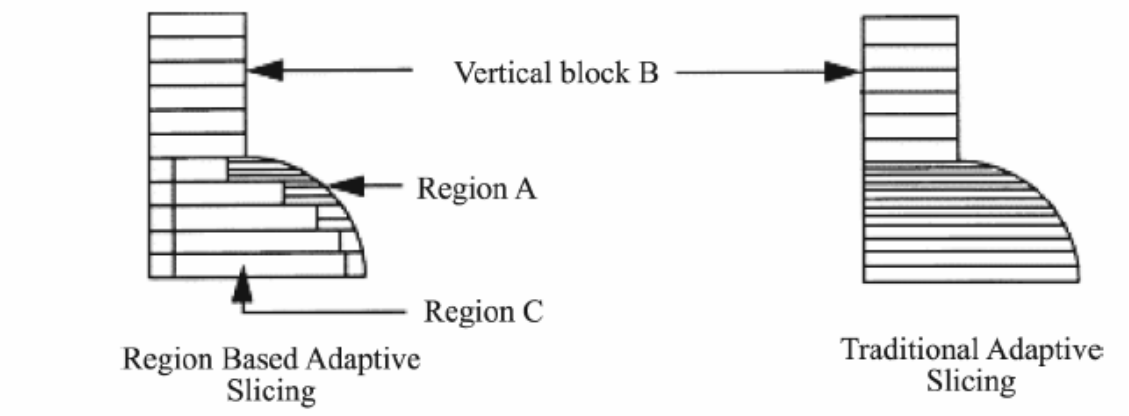


Figure 2.5. Slicing of a model by Region based adaptive slicing traditional adaptive slicing (Mani, Kulkarni and Dutta, 1999).

In RAS, the model is decomposed into two regions A and C. Region A is Adaptive Layer Thickness (ALT) region near the curved surface and is adaptively sliced. Region C is the interior Common Interface Layer (CIL) and is sliced at the maximum thickness. This region based slicing strategy gives the user a control and flexibility over the surface quality of all surfaces, while ensuring the fastest manufacture of the part for the user specified surface requirements.

Weiyin and Peiren (1999) presented an adaptive slicing and selective hatching strategy for RP. This strategy has several important features. First of all, an adaptive slicing approach is used to obtain an accurate and smooth part surface. The developed algorithm operated directly upon a NURBS-based CAD surface model for avoiding possible problems in connection to the commonly used STL interface. A selective hatching strategy is also proposed to reduce the build time by solidifying/depositing kernel regions of the part with the maximum allowable thick layers of a certain RP system. In addition, the strategy provides an iterative solution to the containment problem with mixed tolerances for the slicing of an RP part. This study provided precise skin contours for all layers and for all tolerance requirements.

Lee and Choi (2000) proposed an algorithm that gives an improvement in computing time. It uses contour line intervals between two consecutive slices instead of calculating the slice thickness at each sampled point. The calculation efficiency is further improved by introducing the vertical character lines of the model. The results in terms of accuracy and speed are compared with the existing methods.

Xu, Loh and Wong (1999) presented an adaptive slicing method similar to that due to Kulkarni and Dutta, which slices CAD models represented by analytical surfaces. They used Genetic Algorithms (GA) to find out layer thickness at z = constant contours, where z is the direction of deposition. In their work, build time was estimated by the ratio of number of adaptive slices to largest possible number of slices, accuracy was estimated by ratio of overhang area to the total surface area and stability was estimated by the penalty approach. The value of penalty was set equal to zero if the projection of centre of mass of the part lies within the convex hull (at the candidate base plane) otherwise value of penalty was calculated by the ratio of multiplication of closest distance between the Center of Gravity (CG) projection in the base plane to the convex hull of the base and height of the CG of the part to the base plane area. A trading-off among these objectives was performed by choosing suitable values of weights for stability, accuracy and build time to achieve the best orientation

Kumar and Choudhury (2005) calculated the volume deviation between a CAD model and built-up part in 5-axis LOM employing direct slicing with first-order approximation. It is proposed that the deviation between the CAD model and the built-up part, be treated as a volume, for higher accuracy in subsequent calculations. An algorithm has been developed and implemented for identification and calculation of volume deviation considering all possibilities. It has been conclusively shown that volume deviation consideration results in improved feature recognition and less approximation. Calculation of volume deviation would help eliminate the loss of intricate features in a complex surface and thus improve feature recognition. Slice height calculations based on volume deviation would reduce the deviation between the actual model and the built-up part.

The primary benefits of direct CAD model slicing are increased model accuracy and smaller file sizes. Researchers contend that, by slicing the model within the CAD software, exact contours can be derived from the model's true surfaces. In addition, storing the cross-sectional data requires less space than a tessellated model would require (Vuyuri et all.1997, Beaman et all.1997, J. Pickens et all.1998). Also, the need for model repair and a conventional slicing process is eliminated. As a result, many research groups have implemented direct CAD model slicing. Guduri et all. (1992) developed an interface to RP processes based on Constructive Solid Geometry (CSG). In their work, a part to be fabricated is represented by CSG primitives. Each primitive is sliced individually to generate a set of independent contours. Boolean operations are then performed at the intersections of these contours to produce each slice. Slicing high-degree polynomial surfaces (NURBS), on the other hand, is non-trivial and prone to round-off errors. Furthermore, there is currently no standard higher-order geometric description available to exchange geometric data from a particular CAD system to a specified RP fabricator.

The adaptive slicing methods described above are able to improve the efficiency for the fabrication of rapid prototyping parts, but two disadvantages exist. First, their methods in determining layer thickness must calculate the thickness for each sample point at the slice level and then select a minimum value for the actual layer thickness. It is inefficient to calculate a large amount of data, however, only a part of the real data is useful. Second, these methods use the cusp height to measure the error between the CAD model and the part. However, when the normal vector of the model surface becomes perpendicular to the slice level, the error measured using the cusp height becomes questionable. Another method useful for measuring the error is to calculate the distance on the slice layer between the boundary of the CAD model and the boundary of the RP part.

3. MATERIAL AND METHOD

3.1. Process Planning in RP

Process planning steps depend on the part accuracy, build-time, mechanical properties and efficiency requirements. The orientation of a part affects its surface accuracy, build-time, mechanical properties and the need for support structures Cooper, 2001). Thus, the designer has to select the orientation based on the criteria deemed important before slicing the CAD model. The amount of support structures required affects build-time. The slicing process also influences the surface accuracy and build-time/cost. Finally, hatching the slice generates the path to guide the nozzle, to solidify the layer boundary. The path planning also affects the mechanical properties and build-time (Figure 3.1.).

3.1.1. Information Requirements in Process Planning of RP Parts

The basic input to a RP process planning system is the description of the shape of the object to be manufactured. Additionally, tolerance information, surface finish, material data, etc. should ideally be used in performing process planning tasks.

3.1.1.1. Non-Geometric Process Planning Input

Apart from geometrical information, other types of desirable input data include shape tolerances, materials and process information.

Tolerance Information: This includes tolerances of size, location and form, together with associated datum elements where appropriate. However, more important form of tolerance information in RP is concerned with surface finish. In the RP

In general, path planning strategies that include a boundary traversal in addition to a fill pattern give a better surface finish, because they avoid the occurrence of the secondary staircase effects and voids in the slice contours that may arise.

Material Information: Knowledge of material properties and process characteristics is required for all stages of process planning. Slicing calculations require the minimum and maximum allowed layer thickness which varies for each process and often for each material for heterogeneously formed parts. Stiffness of parts built by RP is affected by layerwise deposition of material and also by the fill strategy used in each layer. Hence, the material information can be used to derive an optimal orientation as well as appropriate path planning strategy based on part strength.

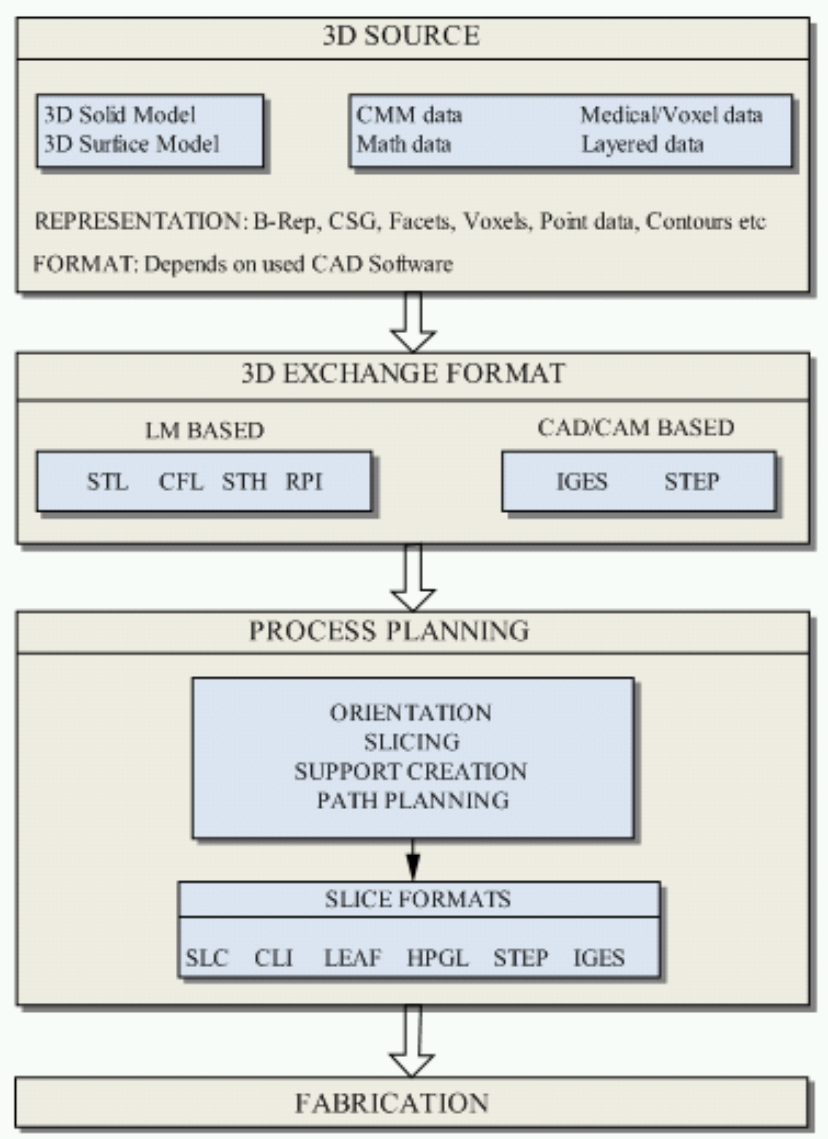


Figure 3.1. Data flow in RP

Process Information: Most of the process planning steps requires information about the RP process to be used. During the support creation, the angle of overhang must be known which is dependent on the RP process. During slicing, the layer thickness range is needed which is dictated by the RP process. In the path planning stage, the road width is based on the RP process to be used. For the fabrication of the part, the speed of the head and the time interval between successive paths is dependent on the RP process. Finally, some RP processes require curing after the part is built. All these information has to be provided during the various stages of process planning.

3.1.1.2. Geometry Related Process Planning Input

The 3D data input for the RP process can be obtained from a wide variety of sources:

- **3D CAD Model:** This model is created by the designer using CAD software in the computer. In general, a CAD model could either be wireframe, solid model or surface model.
- **Reverse Engineering Data:** This form of input is usually obtained by RE where an existing part is to be duplicated. The existing part is scanned using a 3-d shape digitizer (CMMs, optical sensors) to generate points from the surface of the object.
- **Mathematical data:** This form of input is mainly experimental data or data from mathematical programs.
- **Medical/Voxel data**: Medical data are obtained by scanning parts of human body; the only difference being the data is truly three-dimensional, i.e. data is obtained both from the exterior and the interior of the object. The most commonly used methods for getting these data are CT and Nuclear Magnetic Resonance (MR).
- **Computerized Tomography:** CT scan data is a special approach for medical imaging (Jacobs, 1992; Swaelens, 1993). This is not standardized data. Formats are proprietary and somewhat unique from one CT scan machine to another. The scan generates data as a grid of three-dimensional points, where each point has a varying shade of gray, indicating the density of the body tissue found at that particular point.

Data from CT scans have been used to build skull, femur, knee and other bone models on various RP systems. Some of the reproductions were used to generate implants, which have been successfully installed in patients. The CT data consist essentially of raster images of the physical objects being imaged. There are three approaches to making models out of CT scan information: (1) Via CAD Systems (2) STL-interfacing and (3) Direct Interfacing. The main advantage of using CT data as an interface of rapid prototyping is that, it is possible to produce structures of the human body by the rapid prototyping systems. But, disadvantages of CT data include the increased difficulty in dealing with image data as compared with STL data is the need for a special interpreter to process CT data.

- **Layered data:** The 3D data may also be obtained as layers/contours/slices i.e. cross-sections of the shape at different levels. Examples include topographic data, geophysical data (Burns, 1992), engineering data (Marsan, 1996), etc.

3.1.2. 3D Exchange Format

The data transfer is to translate a mathematically represented solid/surface model to a sequence of 2-D cross sectional images which can be used to drive a RP machine. Generally speaking, the data input source of RP systems is from CAD systems. While different CAD software packages have different internal data representations, the exchange of information has been on the same basis, i.e., 2-D drawing or 3-D solid/surface model.

With rapid developments in hardware and software, RP will soon emerge as a mainstream fabrication technology. One of the important tasks PP of RP is slicing which utilize these models to generate layers (2D domain). This layer information is processed further to generate toolpaths (ID domain) for fabrication of objects. The transfer of data from 3D to 2D and then to ID and various stages in each domain becomes important as RP gets adopted by the industry.

3.1.2.1. The STL Format

The STL file format was established by 3D systems in 1987 and it has now become the de facto industry standard (Bohn, 1993; Burns, 1992, Kumar 1997, Kevin 1999). An STL file approximates the shape of a solid model using small triangles called facets. The smaller the facet sizes, the better the surface approximation, but the expense of file size and processing speed. An STL file contains a list of X, Y and Z coordinate triplets that describe a surface mesh of triangular facets. The RP system uses the stack of digital cross sections to produce each layer of material, one on top of the next. The STL format is shown in figure 3.2. The STL file format includes both an ASCII and a binary version. However, they are not fully compatible. The binary version has additional attribute information which is not used currently. The ASCII format is meant for debugging and test purposes.

The use of STL format has certain advantages:

- **Easy conversion:** It is very simple as it contains only a list of planar triangles. The conversion of a 3-D model to the STL format is done using the standard surface triangulation algorithms. These algorithms are known to be simple, robust and reliable when compared with other approximations.
- **Wide range of input:** Any form of 3D geometry can be converted to a triangulated model due to the wide applicability of the available surface triangulation algorithms.
- **Simple slicing algorithm:** The algorithm for slicing an STL model is usually simple but not necessary efficient as it only involves processing a list of triangles.

Despite the above mentioned advantages, the conversion of a 3D model to STL format has several drawbacks (Furrens, 1999; Dolenc, 1994; Jamieson, 1995; Bohn, 1995; Lrong et all., 1996; Jurrens, 1993; Kumar et all, 1997; Sabourin et all., 1996).

- **Verbose:** STL file is verbose and has redundant data such as normal information and repetition of vertex data.
- **Approximation:** A major problem with the triangulated boundary

representation is that curved surfaces can only be approximated by triangular facets. A large number of facets give high approximation accuracy, but results in an extremely large amount of data. A smaller number of facets allows for less data but lacks accuracy.

- **Truncation:** The original CAD model which is represented in double precision is converted to single precision while generating the STL data. Hence, with the absence of topological information in the STL model, truncation errors become significant.
- **File size:** STL file sizes are unnecessarily large because of redundancy in the file format. Facet normal information is redundant, since the semantics of the representation allow this to be calculated from the ordered vertex list of each facet. Also, the great majority of vertices are multiply specified in the file, since they belong to more than one facet. It would be more efficient to specify each vertex once and make reference to it from each owning facet.
- **Lack of information:** The original 3D model, in general, is complete with geometry/ topology information. By converting it to STL format, only the basic geometry information is stored and other information are neglected.
- **Gaps**: Surface facets connect to form a set of closed shells that enclose or exclude material. If any facet is missing, then the shell is punctured, leaving a gap and there is no clear distinction between the inside and the outside the object. When a faceted model with gaps is sliced, the slices contain non-closed contours and scan path vectors may extend beyond the boundary of the desired object.
- **Inconsistent and incorrect normals:** Facet normals could be flipped and thus be inconsistent with the orientation of other facets. Also, facet normals may not be the same as the normal computed from the facet's vertices.
- **Incorrect intersections:** Facets may intersect at incorrect locations (apart from their edges) i.e. overlapping facets.
- **Internal walls and structures:** These could be generated by faulty geometric algorithms while closing gaps in STL and can cause discontinuities in the solidification of the material.

- **STL Repair:** Due to the previously mentioned problems, additional operations/manipulations have to be performed on the STL model to guarantee the correctness of the model which is very computational intensive.

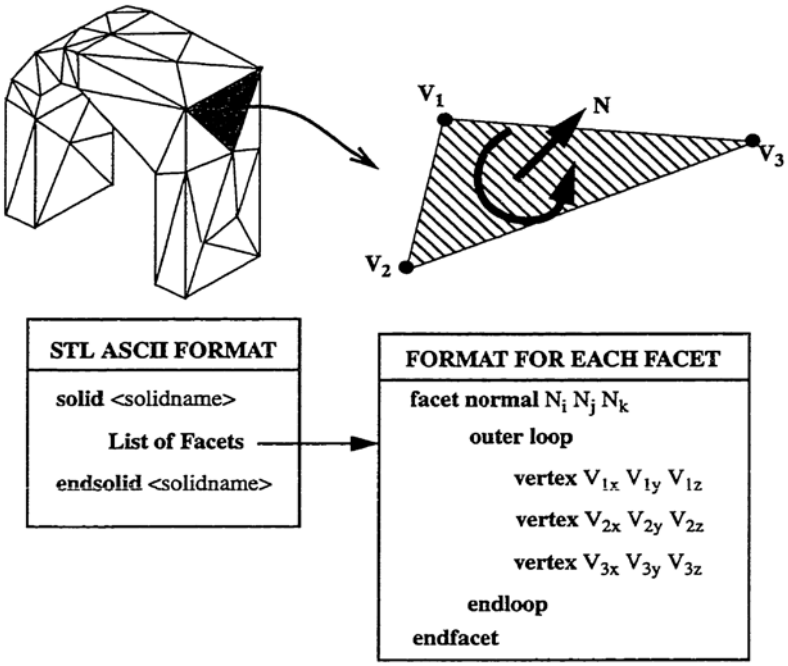


Figure 3.2. STL format (Kai and Fai, 1998)

Much time and effort is currently spent in correcting faulty STL files and generating topological information from the facets. It has been estimated that about 10% of STL files formed from solid models have flaws, while 90% of those formed from surface models exhibit problems.

3.1.2.2. Alternatives to STL

Over the last decades, significant advances have been made in all aspects of RP technology, including hardware, software and materials. New materials and process capabilities have expanded the application domain of RP beyond rapid prototyping to the manufacture of tooling, and to the production of one-off or short run functional parts. Consequently, the nature of the information transmitted to the

RP process planning system has become more critical. The automation of process planning algorithms ideally requires more accurate geometrical information than is provided by STL, together with topological and process information. Such requirements cannot be met by the triangulated boundary representation of the purely geometric STL format. These facts, together with the drawbacks of the STL format, provide the motivation for developing alternative input formats for RP process planning systems.

Several alternatives to STL have been proposed in the literature to address the various disadvantages of STL.

Surface Triangles Hinted Format (STH): It uses surface triangulation (like STL) with flexible rules for efficient storage of vertex and connection information (Marsan and et all., 1998). It is more compact and contains optional structural information on source volumes and surfaces.

Cubital Facet List (CFL): This format was developed by Cubital to overcome the problems with STL (Wohler, 1995). It defines a general planar-faceted polyhedral boundary representation, in which facets may contain multiple polygonal holes. The coordinates of all the vertices are stored and indexed. The facet descriptions reference the vertices by their indices and not by value. This saves space and also implicitly captures the connectivity relations between facets in the model. The format also has provisions for storing textual comments, unlike STL, allows for the alternative description of a model as a series of contour slices. Apart from this extension beyond the STL capability, this format possesses both geometry and topological information of the model. CFL files are several times smaller than equivalent STL files.

Rapid Prototyping Interface (RPI): The RPI format is capable of representing facet solids, but it includes additional information about the facet topology (Rock and Wozny, 1991). Topological information is maintained by representing each facet solid entity with indexed lists of vertices, edges and faces. Instead of explicitly specifying the vertex coordinates for each facet, a facet can refer to them by index numbers. This contributes to the goal of overall redundant information reduction.

The RPI format offers a number of features unavailable in the STL format. The format can represent CSG primitive models as well as facet models. Both can be operated by the Boolean union, intersection and difference operators. Provisions for solid translation and multiple instancing are also provided. Process parameters, such as process types, scan methods, materials and even machine operator instructions, can be included in the file. Facet models are more efficiently represented as redundancy is reduced. The flexible format definition allows storage and processing cost to be balanced.

The disadvantage of the RPI format is that more complex than the STL format. Surface patches suitable for solid approximation cannot be identified in the RPI format.

Geometric Workbench for Rapid Prototyping (G-Worp): It has not been proposed as an alternate 3D or slice format (Chandru and Manohar, 1994). However, it does possess representations and formats for storing a 3-D model and a slice. G-WoRP uses the voxel and the slice as primary primitives to represent the model. The voxel primitive is used for 3-D representation of the model from which slices are generated for RP. As the initial model is voxel/slice based, the designer has to think in terms of voxels and slices which is not very intuitive. The boundary information of the model is not stored explicitly and has to be computed. Also, true parametric surfaces cannot be represented using this method. However, the internal volume information of the model, which is normally absent in most representations.

As a comparison; considering alternatives to STL, STH improves on the STL by storing more information and using better storage schemes. But, it does not have the capability to store a polyhedral model. Both CFL and RPI can store a polyhedral model. However, the use of a polyhedral representation of a 3-D geometry has its own drawbacks. The RPI format has the flexibility to define new entities and can store process specifications neither of which is fully available in CFL.

3.1.3 Slice Formats for RP

The use of models with exact rather than faceted geometry allows increased accuracy. This implies that slicing may be done in the CAD system where the design model originates, because that provides the necessary capabilities for accurate geometric computation. In this case, a neutral format is needed for the transfer of the resulting slice data from the CAD system into the RP PP system.

A slice format must enable the capture of all the geometrical data of the layer (Kumar and Dutta, 1997; Rajagopalan et all., 1995). Also, it must have provision to store material and process-related information, if necessary. Currently, there does not exist any industry standard for a slice format. A slice standard must provide a common basis for communicating layer information (Figure 3.3.). Some of the slice formats are discussed below:

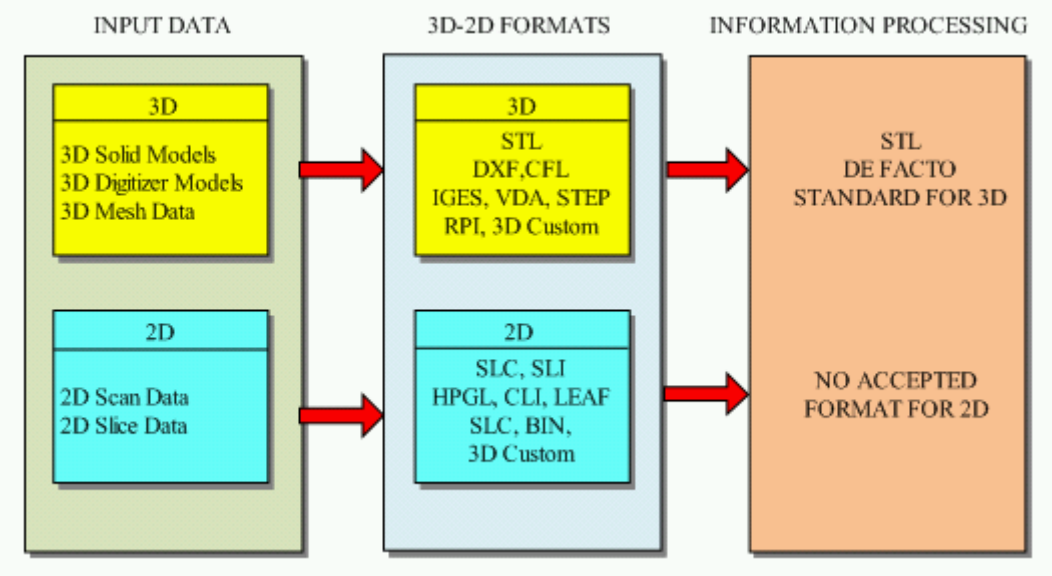


Figure 3.3. 3D and 2D slice formats

Common Layer Interface (CLI): This format was developed in a BRITE/EURAM project (Krause and et all, 1997; Jamieson and Hacker, 1994). CLI is intended as a simple, efficient and unambiguous format for data input to all RP systems. The CLI file can be in binary or ASCII format. The geometry part of the file is organized in layers in the ascending order. Every layer is started by a

layer command, giving the height of the layer. Each layer is represented by its thickness and a set of contours. Contours define the boundaries of the solid material within a layer and are represented by polylines. Each contour should be closed and should not intersect itself or other contours. A hatch is a set of independent straight lines, each defined by a start and an end point. The purpose of hatches and open polylines is to define support and filling structures. There are no non-geometric commands in CLI.

CLI format has some advantages that; supports polyline entities, it is a simpler format compared to the other format. Also, the error in the layer information is much easier to be correct than that in the 3D information. Automated recovery procedures can be used and if required, editing is also not difficult.

However, there exist several disadvantages of the CLI format. It only has the capability of producing polylines of the outline of the slice. Although the real outline of the part is obtained, by reducing the curve to segments of straight lines, the advantage over the STL format is lost.

Layer Exchange ASCII Format (LEAF): The format consists of two sections - the header section and the geometry section (Dolenc and Makele, 1992). The header section defines the preprocessing instructions, mathematical arrangements and technological arrangements. These arrangements are necessary for the geometry section. The preprocessing instructions contain keyword definitions and machine specific information. The mathematical arrangements define the radix of the number system used, units and ranges of values. The technological arrangements define the structure of hatches and supports. These arrangements can be directly referenced by the geometry section instead of stating it explicitly each time. The geometry section is the layerwise geometrical data of the model. The layer is the main entity used and it contains both geometry data and process data. The layer entity can have sub-entities such as region, contour, hatch, support, etc. Each contour is a non-self-intersecting polygon described in terms of 2-D primitives, the polyline and the circular arc.

The advantages of the LEAF format are; easy to implement and use, not ambiguous, allows for data compression and for a human-readable representation,

machine independent and RP process independent, slices of CSG models can be represented almost directly in LEAF and the support structures can be easily separated from the original part.

The disadvantages of the LEAF format include; the new interpreter is needed for connecting the RP systems, the structure of the format is more complicated than that of the STL format and the STL format cannot be changed into this format.

Hewlett Packard Graphics Language (HP/GL): It is a standard data format for graphic plotters (HP-GL Reference Guide, 1990). Data types are all two-dimensional, including lines, circles, splines, texts, etc. The approach can be automate a slicing routine which generates a section slice, invoke the plotter routine to produce a plotter output file and then loop back to repeat the process.

The advantages of the HP/GL format are that a lot of commercial CAD systems have the interface to output the HP/GL format and it is a 2D geometry data format which does not need to be sliced. However, there are two distinct disadvantages of the HP/GL format. First, because HP/GL is a 2D data format, the files would not be appended, potentially leaving hundreds of small files needing to be given logical names and then transferred. Second, all the support structures required must be generated in the CAD system and sliced in the same way. HP-GL is capable of representing an arbitrary 2-D shape filled with any pattern. Hence, it can be used to represent slices and can also be used to drive the RP machine like any plotting device.

The StereoLithography Contour (SLC): There are a several slice formats that are referenced SLC. However, each was developed by a different RP company (e.g., 3D Systems SLC, POGO SLC and Stratasys SLC (FDM System Documentation, 1998)). All of them are proprietary. A typical SLC format is shown in figure 3.4.

SLC attempts to solve problems by taking two-dimensional slices directly from a CAD model instead of using an intermediate tessellated STL model. These slices eliminate the facets associated with STL files because they approximate the contours of the actual geometry. Two problems may arise from this approach. Firstly, in slicing a CAD model, it is not always necessarily more accurate as

the contours of each slice are still approximations of the geometry. Secondly, slicing in this manner requires much more complicated calculations and, is very time-consuming when compared to the STL files.

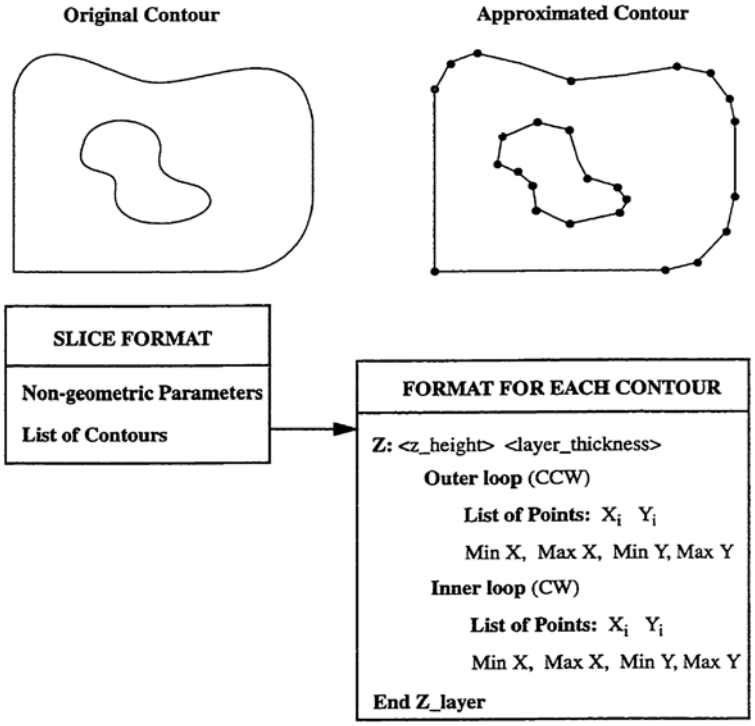


Figure 3.4. Slice format description for SLC

Initial Graphics Exchange Specification (IGES): It is a generally used data transfer medium which interfaces with various CAD systems (Reed and et all., 1990). The IGES file can precisely represent CAD models. It includes not only the geometry information (Parameter Data Section) but also topological information (Directory Entry Section). In the IGES, surface modeling, CSG and boundary representation (B-rep) are introduced. Especially, the ways of representing the regularized operations for union, intersection, and difference have also been defined.

The advantages of the IGES standard are its wide adoption and comprehensive coverage. Virtually every commercial CAD/CAM system has adopted IGES implementations. Furthermore, it provides the entities of points,

lines, arcs, splines, NURBS surfaces and solid elements. Therefore, it can precisely represent CAD model.

However, several disadvantages of the IGES standard in relation to its use as a RP format include; because IGES is the standard format to exchange data between CAD systems, it also includes much redundant information that is not needed for RP systems and the algorithms for slicing an IGES file are more complex than the algorithms slicing a STL file.

Standard for the Exchange of Product Model Data (STEP): STEP, based on ISO Standard 10303 (Dutta et all., 1998; Helpenstein, 1993; Gilman and Rock, 1992), is an international standard for the exchange of product life-cycle data, covering design, analysis, manufacture, maintenance and disposal. STEP has three-level architecture, conceptual, application and physical layers. The conceptual layer contains Integrated Resources (IRs), sets of related data entities that can be specialized to describe different domains of interest. For example, one IR (ISO 10303-42-'Geometrical and topological representation') contains wireframes and surface models with or without topology, faceted Breps, advanced Brep solids and 2D and 3D CSG shape representations. The faceted Brep capability includes that of STL, but uses a more efficient and less error-prone format. The wireframe facility could be used in RP, for the capture of slice contours and tool paths. In the application layer, subsets of the IR data entities are specialized for particular product classes and life-cycle stages. These results in a series of Application Protocols (APs) that prescribe the scope and representation of the data that can be exchanged. The physical layer of STEP architecture defines how the data elements are mapped into a physical file format (ISO 10303-21), or how it may be accessed in a data repository (ISO 10303-22).

The current status of data formats used in RP can be summarized as:

- Currently, STL is used as a standard for RP though it was never intended to serve as one. Also, STL is an incomplete geometrical representation and possess no topological as well as process related information. Alternatives to STL though eliminate certain pitfalls of STL are insufficient to satisfy the data transfer needs of RP.
- There exist no standard for representing layer information (i.e., slice data). A

standard is required as it would provide a common basis for transfer of data during the various stages of process planning in RP.

3.1.4. Reasons for Alternative Representations

The reasons for supporting the new format include the following:

- The CAD model could be analyzed directly to determine an optimum build direction and the required support structures. Then, it could be sliced. Alternatively, the CAD model could be sliced first and the support structures created by analyzing the slices. These operations could be performed using capabilities of the CAD system used.
- CAD models based on precise geometry representation (such as NURBS-based Brep used in this study) could be used to represent slice data without the loss of precision inherent in STL. Hence, direct slicing of such models can give parts with improved surface finish. It may also lessen the time needed for PP, since in order to achieve similar accuracy using STL a fine level of discretization must be used in generating the STL file. This results in a very large file and increases the chances of numerical problems in the triangulation and slicing algorithms.
- CAD systems could take advantage of their proprietary capabilities to optimize the slice algorithm and validate the results. This would avoid the generation of an STL file and the possible need to correct errors in it before transfer to the RP system.
- The data storage requirement of the STL file would be eliminated.
- In most cases, correction of faulty geometry is easier and quicker in sliced data.

The advantages are not intrinsic to the slice format itself, but arise mainly from the drawbacks of triangulated boundary representations and the current need to convert into that form from other representations. The initial input to process planning should not be a triangulated boundary representation, but some format more closely related to the original part data, i.e., an exact CAD model or a set of digitized data points. This would obviate the need for a 3D model transfer in cases where

slicing is performed directly in a CAD or other external system, but that 3D capability needs to be retained for other cases in the interests of flexibility.

On the basis of the considerations given in this section, we recommend the adoption of NURBS representation of a part as input to PP for RP. This may be oriented and sliced in the originating CAD system, but a neutral format must be provided for the 3D representation. A standard format for slice data is also needed, to allow the transfer of slice representations, either between an originating CAD system and a RP PP system or between different RP systems.

3.1.5. Initial Graphics Exchange Specification (IGES)

With the development of CAD/CAM sytems, the data exchange of product among different CAD systems and other application systems has long been a problem. To solve the problem, a reasonable idea is to define a file format that all systems could understand (i.e., read and write). Then, when one CAD system need to exchange data of product with other CAD systems or application systems, the sender would produce the neutral data file for the receiver to read. Based on this, many schemes have been propounded; one of these schemes is Initial Graphics Exchanges Specifications. IGES first emerged in U.S., 1981, it provides a data format for describing product design and manufacturing information that has been created and stored in computer readable form. The IGES format is designed to be independent of all CAD/CAM systems.

3.1.5.1. Product Definition in IGES

The product definition includes geometric, topological and non-geometric data. The geometry part defines the geometric entities to be used to define the geometry. The topology part defines the entities to describe the relationships between the geometric entities. The geometric shape of a product is described using these two parts (i.e. geometry and topology). The non-geometric part can be divided into annotation, definition and organization. The annotation category consists of

dimensions, drafting notations, text, etc. The definition category allows defining specific properties of individual or collections of entities (Table 3.1.)

Table 3.1. Geometric and Non-geometric entities in IGES

Geometric entities :	100, 102, 104, 108, 1 10, 112, 114, 116, 118, 120, 124,126, 128, 142, 144.
Non-geometric entities:	106, 302, 304, 308, 314, 320,402,404,406,408,410,412,414,420.

The purpose of pre-processing is to read in an IGES file and get the suitable entities from it. It is actually a filter process. After the preprocessing, all suitable entities will be read/write in. Table 3.2. list the entities which may be used mostly to define a B-rep structure in an IGES file. Details of the IGES data structure is presented in Appendix C.

Table 3.2. Curve and Surface Entities in IGES

TYPE	NAME
100	Circular Arc
102	Composite Curve
104	Conic Arc
106	Copious Data
110	Line
112	Parametric Spline Curve
114	Parametric Spline Surface
118	Ruled Surface
120	Surface of Revolution
122	Tabulated Cylinder
124	Transformation Matrix
126	Rational B-Spline Curve
128	Rational B-Spline Surface
142	Curve on a Parametric Surface
144	Trimmed Parametric Surface

IGES was originally developed for the exchange of drafting data like 2D/3D wireframe models, text, dimensioning data and surfaces. The IGES provides the following capabilities:

- Geometry: 2D/3D wireframes, 2D/3D curves and surfaces, CSG, B-Rep;

- Presentation: Drafting entities for technical drawings;
- Application dependent elements: Piping and electronic schematics;
- Finite Element Modeling: Elements for FEM systems.

3.1.6. Curve and Surface Background

This section evaluates several geometric representations of curves and surfaces used to model CAD components. Curves and surfaces can be mathematically represented explicitly, implicitly or parametrically

3.1.6.1. Explicit and Implicit Curves and Surfaces

There are common methods of representing curves and surfaces: explicit and implicit equations (Farin, 1991; Piegl, 1994). An explicit representation of a 2D curve has the form y = f(x) and is not used very often in computer aided graphics and geometry design, because such curves are axis dependent and are single valued in y. Implicit representations are of the forms f(x, y) = 0 for planar curves and f(x, y, z) = 0 for surfaces. These equations represent implicit relationships between the x and y coordinates for curves and between the x, y and z coordinates for surfaces. Implicit curves and surfaces are used in some applications, typically for low-degree cases such as degree one or two. Implicit form makes it easy to determine if a given point lies on a curve or surface, whereas parametric form makes it easy to compute points on a curve or surface.

3.1.6.2. Parametric Curves and Surfaces

Parametric curves in the plane are given by;

$$C(u) = (x(u), y(u)) \tag{3.2}$$

where each of the coordinates of a point on the curve is represented separately as a function of the parameter u. Parametric surfaces are represented in the biparametric form;

$$S(u,v) = (x(u,v), y(u,v), z(u,v)) \tag{3.3}$$

where the two parameters u and v are needed to define the surface. An isoparametric curve is generated by holding one parameter constant and varying the other parameter through the domain of the surface.

3.1.6.3. Ruled Surfaces

Ruled surfaces can be defined using two parametric curves called directrices. A ruled surface is generated by sweeping a straight line along the two directrices. If one of the directrices is a point, the ruled surface degenerates to a cone. The parametric equation of a ruled surface is:

$$S(u,v) = (1-v)P(u) + vQ(u) \tag{3.4}$$

where P(u) and Q(u) are the directrices. Therefore, the ruling joining two points $Q_i = Q(u_i)$ and $P_i = P(u_i)$ is simply:

$$S(u_i, v) = P_i + v(Q_i - P_i) \tag{3.5}$$

3.1.6.4. Bezier Curves and Surfaces

Bezier curves have become the foundation of parametric freeform curve and surface geometry in CAD and visualization (Rogers, 2000; Piegll and Tiller, 1997). All CAD systems allow creation and manipulation of B-splines. A Bezier curve is defined by a series of two or more control points. The control points make up what is

called the control polygon. Linear segments that connect the ordered series of control points form the control polygon.

Bezier curves have an associated degree. The degree, *n*, of a Bezier curve is: $n = m - 1$, where *m* is the number of control points. Thus, a first degree Bezier curve has two control points; a second degree Bezier curve has three control points, etc. Examples of Bezier curves are included in figure 3.5. The control polygons are shown as lines connecting the control points. The shape of the Bezier curve is completely defined by the location of the control points. By moving the control points, the curve changes in a unique, mathematically defined manner.

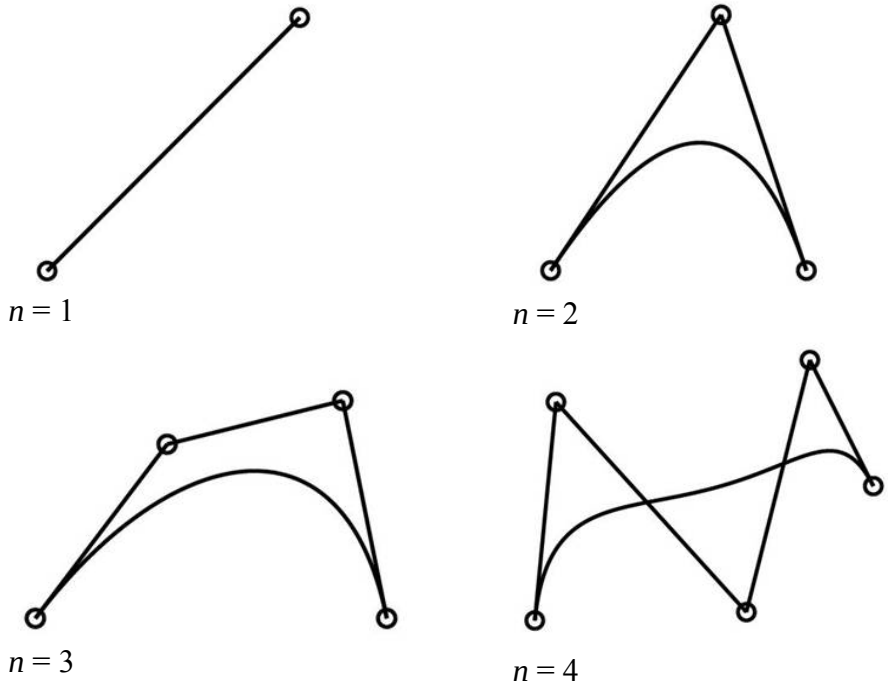


Figure 3.5. Bezier curves (Soderberg et all., 1990)

Bezier curves and surfaces have several advantages for geometric modeling. The first and last control points are coincident with the endpoints of the curve segment. The curve is also tangent to the first and last edges of the control polygon and the curve generally follows the shape of the control polygon, making it intuitive to modify. Bezier curves can also be strung together, providing automatic continuity between the endpoint of one Bezier curve and the starting point of another Bezier curve.

Although several Bezier curves can easily be strung together with C^0 continuity, it is somewhat difficult to construct a set of C^2 Bezier curves or C^2 Bezier surface patches. These limitations are addressed by the use of B-Splines.

3.1.6.5. B-Spline Curves and Surfaces

The use of B-Spline curves and surfaces in geometric design was first proposed by Gordon and Riesenfeld (Gordon, 1974; Riesenfeld, 1973). B-Splines originated in the field of approximation theory. "B-spline" stands for "basis spline" and degree p B-spline basis functions span the space of $C^{\{p-1\}}$ splines. A degree p B-spline curve can be thought of as a collection of degree p Bezier curves that generally meet with $C^{\{p-1\}}$ continuity. The parameter values at which adjacent Bezier curves meet are called knots.

Normally, a single Bezier curve is insufficient to define a complex geometric shape. The impetus for the development of B-splines was the desire and need to maintain a level of continuity between two or more freeform curves. Two types of continuity exist: parametric (C^i) and geometric (G^i) continuity. Curves that are parametrically continuous at the i^{th} level have identical parametric derivatives, meaning both magnitude and directions are matched at the i^{th} level. Additionally, all lower-order derivatives are parametrically identical. Curves that are geometrically continuous at the i^{th} level have identical directional derivatives at the i^{th} level and all lower levels.

B-splines offer the mechanism by which Bezier curves can be automatically connected while maintaining a level of continuity. B-splines are a mathematical coupling of a series of Bezier curves such that C^{n-1} continuity is always preserved between individual Bezier segments. A b-spline has control points and a control polygon like individual Bezier curves, but is also regulated by a knot vector. The number of control points, *cp* is calculated as: $cp = n + m$, where n is the degree of the Bezier segments and m is the number of Bezier segments. The knot vector of the

b-spline maintains information concerning the parameter ranges of each underlying Bezier curve. Figure 3.6. depicts a B-spline with its control polygon.

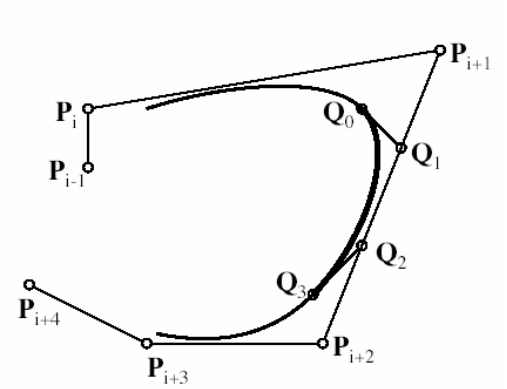


Figure 3.6. Control polygon of a single Bezier curve (Piegl, 1997)

The equation of a p[th] degree B-Spline curve is;

$$C(u) = \sum_{i=0}^{n} N_{i,p}(u) P_i \qquad a \le u \le b \tag{3.6}$$

where P_i are the control points. The p[th] degree B-Spline basis functions are given by the recurrence relation;

$$N_{i,0}(u) = 1 \text{ if } u_i \le u < u_{i+1}, \text{ or 0 otherwise} \tag{3.7}$$

$$N_{i,p}(u) = \frac{u - u_i}{u_{i+p} - u_i} N_{i,p-1}(u) + \frac{u_{i+p+1} - u}{u_{i+p+1} - u_{i+1}} N_{i+1,p-1}(u) \tag{3.8}$$

A tensor product B-Spline surface is defined by;

$$S(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{m} N_{i,p}(u) N_{j,q}(v) P_{i,j} \tag{3.9}$$

where p and q are the degrees in the u and v directions, n and m are the number of control points in the u and v directions, and the basis functions are as in (3.7 and 3.8).

There is a relationship between the number of knots, the degree, and the number of control points in a B-spline curve: $m = n + p + 1$, where p is the degree, n is the number of control points, and m is the number of knots. A nonperiodic knot vector U is denoted by;

$$U = \left\{ \underbrace{a,...,a}_{p+1}, u_{p+1},...,u_{m-p-1}, \underbrace{b,...,b}_{p+1} \right\} \text{ subject to } x_i \le x_{i+1} \tag{3.10}$$

For B-Spline surfaces, two knot vectors are required (one for each parameter), where the number of knots in the knot vectors is determined based on the relationships $r = n + p + 1$ and $s = m + q + 1$. Knot vectors U and V can be represented by:

$$U = \left\{ \underbrace{a,...,a}_{p+1}, u_{p+1},...,u_{m-p-1}, \underbrace{b,...,b}_{p+1} \right\} \text{ subject to } x_i \le x_{i+1} \tag{3.11}$$

$$V = \left\{ \underbrace{a,...,a}_{q+1}, v_{q+1},...,u_{s-q-1}, \underbrace{b,...,b}_{q+1} \right\} \text{ subject to } x_i \le x_{i+1} \tag{3.12}$$

Because the B-Spline basis is a generalization of the Bernstein basis, many favorable properties found in Bezier curves and surfaces are also found in B-Spline curves and surfaces. B-Spline curves and surfaces tend to follow their respective control polygon, similar to Bezier curves and surfaces. B-Spline curves and surfaces also exhibit Bezier end conditions when the knot vectors are clamped, i.e., when the first and last knots have multiplicity p+1 for curves, and multiplicity p+1 and q+1 for surfaces.

B-Spline curves and surfaces also exhibit some favorable properties that any one single Bezier curve or surface does not. Because they are composed of several different polynomial curves, local manipulation of a B-spline curve or surface can be

done without affecting the whole curve or surface and while maintaining automatic continuity.

3.1.6.6. NURBS Curves and Surfaces

Rational B-Spline curves and surfaces were first proposed for use in design by Versprille (Versprille, 1975). NURBS (Non Uniform Rational B-Spline) curves and surfaces have now become widely used for geometric design. A NURBS curve can be viewed as the projection of a nonrational (polynomial) B-Spline curve defined in four-dimensional homogeneous coordinate space back into a three-dimensional physical space (Rogers, 2001; Piegl, 1994; Piegl and Tiller, 1997; Farin, 1991). A p^{th} degree NURBS curve is defined by;

$$C(u) = \frac{\sum_{i=0}^{n} N_{i,p}(u) w_i \boldsymbol{P}_i}{\sum_{i=0}^{n} N_{i,p}(u) w_i} \qquad \text{for } a \le u \le b \tag{3.13}$$

where P_i are the control points, n+1 is the number of control points, the p^{th} degree B-Spline basis functions and the nonperiodic knot vector are the same as for B-Splines, and w_i are the weights. Similarly, a p^{th} degree NURBS curve can be represented in homogeneous form by;

$$C^w(u) = \sum_{i=0}^{n} N_{i,p}(u) P_i^w \tag{3.14}$$

where

$$P_i^w = \left(w_i x_i, w_i y_i, w_i z_i, w_i\right)$$

A NURBS surface of degree p in the u direction and degree q in the v direction is defined by;

$$S(u,v)=\frac{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)w_{i,j}P_{i,j}}{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)w_{i,j}} \qquad 0\le u,v\le 1 \tag{3.15}$$

$P_{i,j}$ are the control points that form a bidirectional control net, $w_{i,j}$ are the weights, and $N_{i,p}(u), N_{j,q}(v)$ are the nonrational B-Spline basis functions defined on the knot vectors:

$$U=\left\{\underbrace{0,\ldots,0}_{p+1},u_{p+1},\ldots,u_{r-p-1},\underbrace{1,\ldots,1}_{p+1}\right\} \qquad u_i\le u_{i+1} \tag{3.16}$$

$$V=\left\{\underbrace{0,\ldots,0}_{q+1},v_{q+1},\ldots,u_{s-q-1},\underbrace{1,\ldots,1}_{q+1}\right\} \qquad v_i\le v_{i+1} \tag{3.17}$$

with the relationships $r=n+p+1$ and $s=m+q+1$. A NURBS surface is also conveniently represented in homogeneous coordinates by;

$$S^{w}(u,v)=\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)P^{w}_{i,j} \tag{3.18}$$

where

$$P^{w}_{i,j}=\left(w_{i,j}x_{i,j},w_{i,j}y_{i,j},w_{i,j}z_{i,j},w_{i,j}\right)$$

NURBS curves and surfaces have all the nice properties of polynomial B-Spline curves and surfaces. However, NURBS have an advantage over polynomial B-Splines in their capability of precisely representing conic sections. Like polynomial B-splines, NURBS curves and surfaces tend to follow the control polygon and exhibit Bezier end conditions when the knot vectors are clamped. Because they are composed of several different curve segments, local manipulation

of a curve or surface can be done without affecting the whole curve or surface. Also, the degree of the NURBS curve or surface is independent of the number of control points.

NURBS curves and surfaces also exhibit desirable properties. They are able to represent more complex geometry than polynomial B-Spline curves and surfaces due to weighted control points. Because each control point is weighted, curves or surfaces can also be changed without varying the position of the control point. The projection of a NURB curve or surface is also a NURB curve or surface. This is a property not possessed by B-Splines, which are only invariant with respect to affine transformations.

In addition, NURBS use a non-uniform knot vector, providing several advantages:

- Continuity can be controlled through using multiple knots,
- Aids in curve fitting routines by allowing users to distribute more control points in complex areas of curves and fewer control points in areas of curves needing less detail.

3.1.7. Extraction of Geometry Data from IGES File

The communications between the CAD systems and RP are crucial. In order to communicate the geometry from RP to CAD, the RP system must have the ability to read in / output to IGES file. However, many of the geometric representations can be transformed to NURBS analytically. The NURBS can be used in RP to model various geometric definitions; it is possible to communicate with the CAD/CAM system through the IGES entities 126 and 128 which are the NURBS curve and surfaces. Hence, the NURBS representation provides the linkage between the RP and CAD system.

This work is carried out by first including the development of algorithms for transforming Non NURBS entities encountered in standard IGES format to NURBS definitions and then following the development of algorithms for easy and efficient

NURBS manipulation, contour generation, layer slicing and part building as shown in figure 3.7.

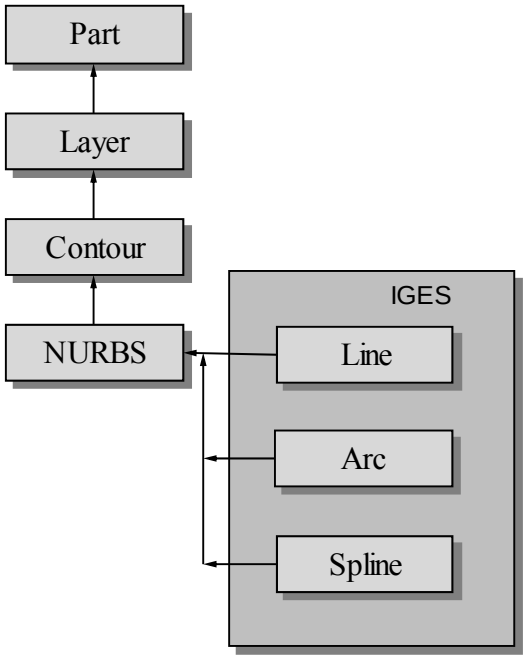


Figure 3.7. Data flow in proposed study

3.1.8. Formulation of Extraction of Geometry Data from an IGES File

One of the prime objectives of this study is extraction of geometry data of CAD models from their IGES. In the IGES file these information are maintained in the form of a set of entities arranged sequentially. Unique numbers identifies entity types. Each entity type has a specific purpose in maintaining the CAD model information in the IGES file. Based on the analysis of modular and structural pattern of an IGES file, C++ based OOP approach has been thought to suit best to extract the geometry data.

Progressing sequentially, starting at line one in the directory section, the surfaces pertaining to the CAD model are sequentially represented by surface entities. Data associated with an entity enable tracing the associated closed curves. A closed curve leads to the associated curve segments and a curve segment leads to the associated points. Collection of all the surfaces pointed by the boundary entities enables defining the complete CAD model. The step-by-step progress from a

boundary entity that leads to eventual collection of all the geometry points defining a model is stated here.

3.2. Program to Extract Geometry Data from IGES File

NURBS stands for Non-Uniform Rational BSpline and is a parametric form consisting of the control polygons, knot vectors, orders and weights to represent the geometric entity accurately. If all the weights of a NURBS entity are equal to one, then it is called a Non-Rational BSpline.

Recently, the IGES entities 126 and 128 have become increasingly popular in geometric definition. This popularity is due to various characteristics of the NURBS, especially the shape preserving property. Many commonly used curve and surface definitions can be analytically represented by NURBS (Figure 3.8.). These commonly used geometric entities include the circular arc, conic arc, line, cubic spline curve, cylinder, ruled surface, surface of revolution, parametric surface and so on. The local control property facilitates the local modification of the geometry without altering the entire geometric shape. This attractive property makes it possible to refine/ reconstruct the desired portion of geometry locally.

Also, the NURBS geometry tool kits which include the knot insertion, degree elevation and splitting algorithms, make NURBS useful in their own right. The knot insertion algorithm is used to increase the associated knot vector without changing the original NURBS shape. After increasing the number of knot values in a knot vector, the designer has more freedom to modify the associated NURBS curve, surface or volume. Similar to the knot insertion algorithm, the degree elevation provides the flexibility to modify the NURBS entity by increasing the associated degree without changing the original geometric shape.

In this thesis, C++ based programming is used to read in the data from the IGES file and write output to a file in the IGES format. Similar to the reading functions, there exists writing functions. The input phase creates objects for each of the entities in the directory entry section of the file and populates the objects with appropriate attribute data.

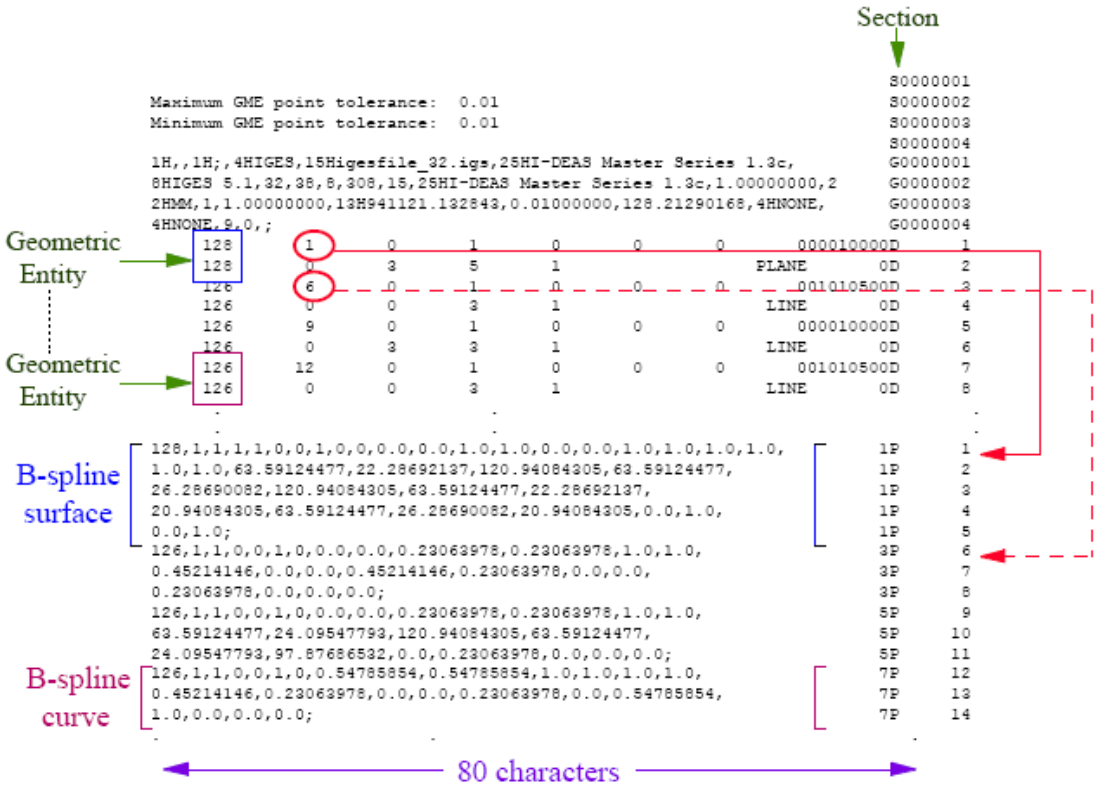


Figure 3.8. IGES format based on B-spline representation

Software is written as a C++ class. The class has private members like a pointer to the IGES file, a file position pointer, the sequence number and the directory entry index of the current record being read and a character array to store the current line being read. Also functions to read a single record, functions to read the common data types like integer, string, double and float, form the private member functions. Other functions that are used to open, close and parse each of the sections of the IGES file are written as public members of the class.

When an IGES file is read, an instance of the I/O IGES class is created. The reader first opens the file for input and function calls are made to read each of the sections. Each record in the file is read into a character string. The length of the record is checked to ascertain that it contains exactly 80 characters. The IGES reader first parses through the start section of the IGES file. Next the global section of the file is read, an object of the type global, which defines all the elements in this section, is created and populated using the data being parsed. The global section

defines the parameter delimiters and the record delimiters which are used throughout the file. The other data contained in the global section is subsequently read.

After the global section is populated, the IGES reader parses through the directory entry section of the file. The directory entry section is parsed in two passes. In the first pass, the record is read and the entity type number is read from that record. The entity number is used to create an instance of an object of that type. A Dictionary of created IGES objects is maintained. The Directory Entry number in the IGES file is converted into a string and this is used as the key to identify the objects. In the second pass, the elements of the directory entry are read in.

The directory entry number of the particular entry is used to index into the Dictionary, retrieve the object and to populate its other data elements. Next, the parameter data section is parsed. The sequence number of the record in the parameter data section is used to retrieve the instance of that particular object. This is the same as the second pass of the directory entry section wherein a unique key is used to retrieve the instance and the data in the record is used to populate the object.

Finally, the terminate section of the IGES file is read and the file closed. The IGES data is now available in the form of objects which are to be converted into NURBS objects.

3.2.1. Transforming Procedures for Non-NURBS Entities to NURBS Curves and Surfaces

Transforming the Non-NURBS geometric curves and surfaces to NURBS definition in the IGES structure is the main topic of this section. To model a NURBS entity, according to the equations (3.16) - (3.21), we have to should define the control polygons (or control net / volume), weights, knot vector(s) and the order(s) as shown in figure 3.9. The procedure presented in this section has been developed to facilitate the communication between CAD/CAM systems that often utilize different formats which makes transfer of information.

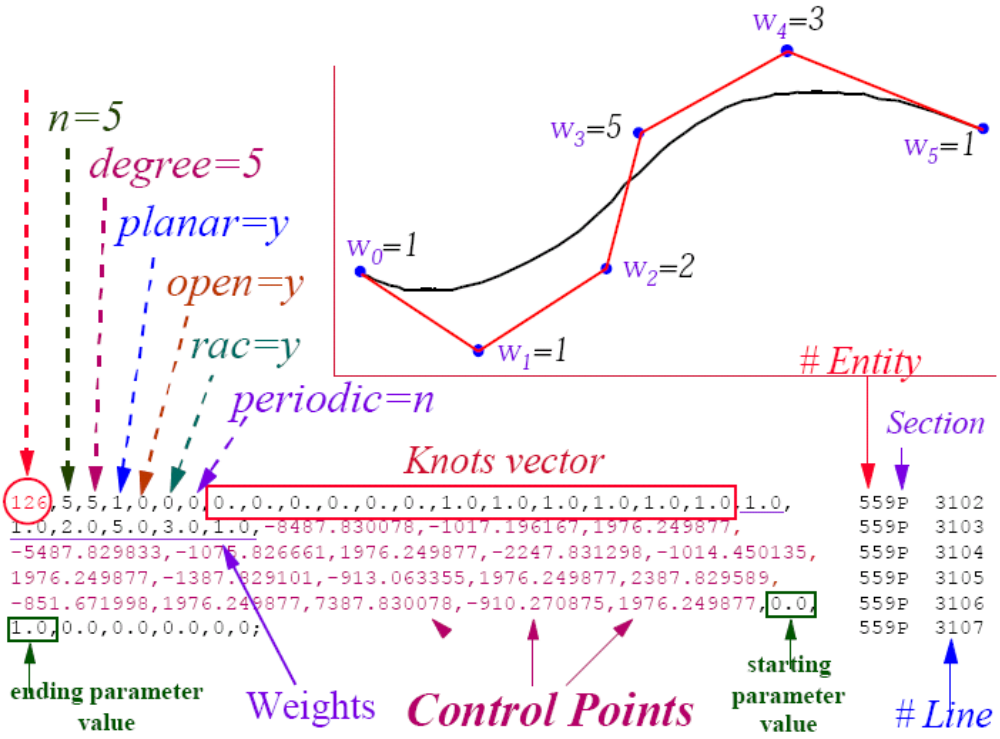


Figure 3.9. IGES format for B-spline curve

3.2.2. Conversion of the Non-NURBS Entities in the IGES to the NURBS Representations

3.2.2.1. Straight Line (110) to NURBS Curve

The first entity to transform is the straight line (entity 110). A straight line is defined as the connection between two 3D data points in the IGES. Therefore, with regard to NURBS, the definition of the line uses the original two points as the two control points (d). Then, set order (k) equal to 2, set weights (W) all equal to 1 and set the knot vector as (0,0,1,1). Since there are only two control points, the n is equal to 1.

3.2.2.2. Circular Arc (Entity 100) to NURBS Curve

A circular arc (entity 100) is represented by a center point, starting point and ending point within a given constant Z plane. The two end points and the center point form an arbitrary sector angle which does not necessarily start from zero. It has been shown that any circular arc with sector angle less than or equal to 90° can be represented by NURBS. The basic control polygon for this NURBS representation is shown in figure 3.10.

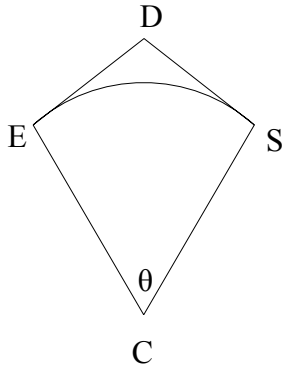


Figure 3.10. Basic control triangle for a circular arc

In Figure 3.10., C is the center point, S is the starting point and E is the ending point. The sector angle SCE (θ) is less than or equal to 90°. The two tangent lines SD and ED intersect at D. The order of this control polygon is three, with the control points S, D, E (hence, the n is 2) and the weights are 1, cos(θ/2) and I respectively. The associated knot vector is (0, 0, 0, 1, 1, 1). A circular arc with sector angle greater than 90° and less than or equal to 180° can be represented by two arcs with one half of the original sector angle. For each of these two sections the previous procedure can be used to evaluate the corresponding control polygon. A 180° circular arc represented by two control polygons is illustrated in figure 3.11.

These two control polygons can be combined and the common point D can be eliminated. The resulting NURBS information is setting the control polygon to SIDBA (hence, the n is 4), the knot vector to (0, 0,0, 1/2, 1/2, 1, 1, 1) and the weights to (1., cos(θ /n), 1., cos(θ /n), 1.) A similar procedure can be used for circular arcs between 180° and 270° (with n equal to 6) resulting in a final knot vector of(0, 0, 0, 1/3, 1/3, 2/3, 2/3, 1,1,1) and weights (1, cos(θ /n), 1., cos(θ /n), 1., cos(θ /n), 1.),

and a knot vector of (0, 0, 0, .25, .25, .5, .5, .75 , .75 ,1,1,1) and weights (1., cos(θ /n), 1., cos(θ /n), 1., cos(θ /n), 1.cos(θ /n), 1.) for arcs between 270 ° and 360 ° for n equal to 8.

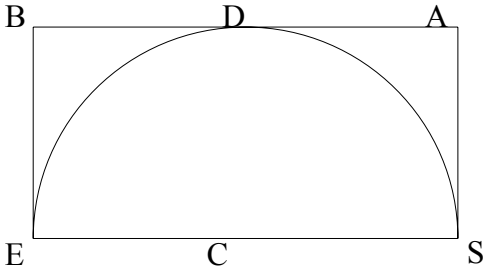


Figure 3.11. The NURBS control polygon

3.2.2.3. Parametric Curve (Entity 112) to NURBS Curve

The cubic parametric curve defined in IGES format is a sequence of parametric polynomial segments. More precisely, it is composed of N (N≥1) pieces of cubic parametric segments as illustrated in Figure C.5.

In Figure Figure C.5., the T(i), i=1, .., N+i are the breakpoints: For this case, N=5, hence, there are 5 cube parametric segments constitute the final curve. For each parametric curve, it is defined as

$$C(u) = a + b\,t + c\,t^2 + d\,t^3 \qquad T(i) < u < T(i+l) \quad \text{and} \quad t = u - T(i) \qquad (3.19.)$$

The cubic Bezier curve is a special case of a BSpline curve with knots vector of (0, 0, 0, 0, 1, 1, 1, 1). Also, the BSpline curve is a special case of NURBS curve with all weights equal to 1. The mathematical transformation from parametric cubic spline curve in IGES definition to NURBS is accomplished as follows:

The matrix form of the each simple cubic parametric curve, according to equation (3.19.), can be expressed as $C(t) = [1\ t\ t^2\ t^3]\ L_{4x4}\ [a\ b\ c\ d]^T$ where L_{4x4} is the identity matrix and $[\ a\ b\ c\ d]^T$ is the transposed matrix containing the coefficients of the cubic curve. The matrix form of the cubic Bezier curve is expressed as $C(t) = [1\ t\ t^2\ t^3]\ B_{4x4}\ [b_o\ b_l\ b_2\ b_3]^T$. The B_{4x4} is the cubic Bezier matrix and $[b_o\ b_l\ b_2\ b_3]^T$ is the transpose matrix containing the Bezier control polygon. The strategy is to first transform the cubic parametric curve to Bezier form, since a Bezier curve can be

treated as the special case of a NURBS curve. Each segment of parametric spline curve is transformed to a Bezier curve by finding the associated Bezier control polygon. This is done by setting the two matrix equations to be equal;

$$\text{Bezier} = \begin{bmatrix} 1 t t^2 t^3 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ -3 & 3 & 0 & 0 \\ 3 & -6 & 3 & 0 \\ -1 & 3 & -3 & 1 \end{bmatrix} \begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \end{bmatrix} = Cubic\,Curve = \begin{bmatrix} 1 t t^2 t^3 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_i \\ b_i \\ c_i \\ d_i \end{bmatrix} = \quad (3.20)$$

Solving the equation (3.6) for the Bezier control polygon. Since the cubic parametric spline defined in IGES is composed of N pieces of cubic curves, the range of parametric value t for each piece is not the same as for the Bezier curve. Hence, a re-parameterization of the cubic parametric curve is necessary.

For each piece of cubic curve, the coefficients $[a_i\ b_i\ c_i\ d_i]^T$ can be obtained from the IGES file, therefore, the final equation to solve (for each segment) is

$$\begin{bmatrix} b_0 \\ b_1 \\ b_2 \\ b_3 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 3 & 0 & 0 & 0 \\ 3 & 1 & 0 & 0 \\ 3 & 2 & 1 & 0 \\ 3 & 3 & 3 & 3 \end{bmatrix} \begin{bmatrix} a_i \\ b_i h \\ c_i h^2 \\ d_i h^3 \end{bmatrix} \quad (3.21)$$

where h = T(i+l) - T(i) and T(i) is the break value defined in the IGES file. After all the Bezier control polygons have been obtained, one can join them together and set the multiplicity of joint knot value equal to 3 to form the final Bspline curve.

3.2.2.4. Composite Curve (Entity 102) to NURBS Curve

A composite curve (entity 102) is defined as a curve entity consisting of lists of constituent curves. Composite curve is a directed curve, which means the direction of the composite curve is induced by the direction of the constituent curves in the following manner. The start point for the composite curve is the start point of the first curve entity appearing in the defining list and the terminate point for the

composite curve is the terminate point of the last constituent curve appearing in the defining list. Within the defining list itself, the terminate point of each constituent curve entity has the same coordinates as the start point of the succeeding curve entity. It is quite difficult to represent the composite curve precisely without transforming all the constituent curves to the NURBS form. After converting all curve entities (like straight lines, circular arcs, conic arcs, parametric curves and rational BSpline curves), the algorithm for all the constituent NURBS curves is performed to form the NURBS representation for the composite curve. The procedure is illustrated as follows:

Suppose two constituent curves C_1 and C_2 form a composite curve. Then, the first step is to perform the degree of elevation of the lower degree curve so that the curves can have the same order. The second step is to adjust the knot vector of the second curve C_2 so that the first knot value of the second curve can have the same value as the last knot value of the first curve. Shifting the knot vector will not change the original NURBS curve, because the basis function is a "normalized" basis function. The third step is to build up the final knot vector by joining the two knot vectors into one knot vector and set that knot value at the joint point to have the multiplicity equal to (order - 1). For example, if the first knot vector is [0,0,0,1,1,1] and the second knot vector is [2,2,2,3,3,3], adjust the second knot vector by shifting -1 to each value. Thus, the second knot vector becomes [1,1,1,2,2,2]. Suppose the order of these two curves are 3, then, the final knot vector should be [0,0,0,1,1,2,2,2]. The fourth step is to match the weights by timing the ratio of (the last weight of the first curve/the first weight of the second curve) to all the weights of the second curve so that the weight at the joint point for the two curve are the same. The last step is to build up the final control polygon and weights by throwing the first control point and weight of the second curve away and jointing the others as one control polygon and one weights vector. After these procedures have been applied to all the constituent curves, a composite NURBS curve should be formed. One more procedure that may apply to this final curve is to perform the knot removal to remove the redundant knot vector. Figure 4.5 shows this procedure for transforming the composite curve

consisting of, from right to left, one straight line, one circular arc, one straight line and one ellipse arc.

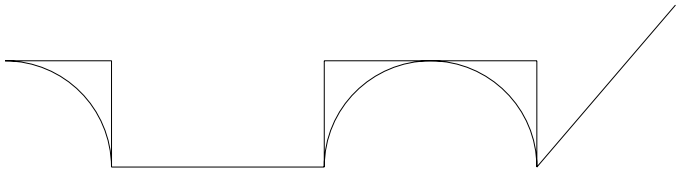


Figure 3.12. NURBS control polygon for a composite curve

3.3. Part Modeling Software

In this study Unigraphics (UG) is used as a part modelling software. The UG can create and edit complex models interactively and with far less effort than more traditional wireframe and solid based systems. Besides this fact, it provides great user development tool (UG/Open API) and an open architecture with UG so as to conveniently developing special user CAD system and user program. Because, it adopts the math base of NURBS, B-spline and Bezier and there are many sorts of means to create various curves and the UG/Open API is a C language interface and the header files are ANSI C compliant and also support the C++ language.

3.4. Development of User Interface

The user interface is created using Qt Designer, a cross-platform, object-oriented C++ Graphical User Interface (GUI) development tool. Qt is motif-based, so dialog windows designed with Qt can be launched from custom CAD/CAM programs. In this study, Qt Designer is integrated with UG modelling package and C++ based developed programs.

In the user interface system, a single menu with pop-up based sub menus is dedicated to each RP preprocessing operation: maximum dimension of the part, part

orientation, slicing both direct and adaptive, supports generation, path planning and fabrication (figure 3.13).

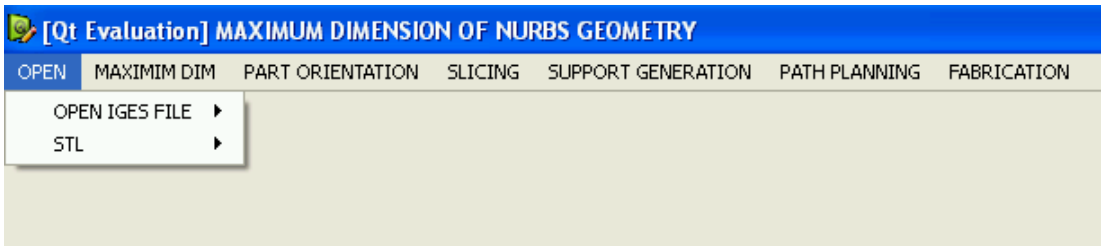


Figure 3.13. Main window of user interface menu

3.5. Programming Software

The structure of program developed in this thesis is object-oriented and is written in C++. There are three main aspects of object-oriented programming: classes, inheritance and polymorphism.

The C++ Class: This part is the heart of an object-oriented C++ program. A class is a container of variables and their related functions. Once a class is correctly defined, the programmer can declare instances of it in the same way he could declare an instance of an int, double or other type of variable. When an instance is declared, all the member variables and functions contained in that class are automatically included. Hence, the class need only be defined once and as many instances of it that the programmer needs can be declared.

Inheritance: This is a way for the programmer to build and add onto classes. Through inheritance, a class may be defined which includes all the variables and functions of a parent class, but adds additional variables and functions unique to itself. Another important property of inheritance allows functions to be declared in the parent class, but the definition of what those functions do are unique to each child class.

Polymorphism: Polymorphism is a powerful way to take advantage of inheritance. When polymorphism is set up correctly, the ability to expand the program and incorporate additional classes and functionality becomes much easier. A

use of polymorphism is that it allows a parent class to have an array of objects, all of which are a different class of object.

3.6. Process Planning Tools for FDM

In this thesis, FDM as a RP technology is used for PP operations. But, this PP steps can be also used easily other RP technologies with little changes. FDM require specialized process planning tools because of the need for simultaneous flow and vector motion control mechanisms (Yardimci, 1996). A schematic description of data flow in FDM is depicted in figure 3.14. Target object described as a two-and-a-half dimensional entity, i.e. collection of two-dimensional layers. Once, the object orientation is determined, layers thicknesses are generated by IGES based NURBS models directly and adaptively, supports and tool paths are generated and finally part is built.

3.6.1. Part Orientation

The determination of the optimal part orientation is essential for all RP processes. Different factors that can be considered while choosing the build direction (Byun et all, 2005; Alexander et all., 1998; Chneg et all., 1995; Patri et all., 2003):

(1) The part's height in the build direction: For many processes the height is directly related to the total build time and hence to the part's final cost. Assuming that the time required to manufacture a layer is essentially the same irrespective of the complexity of path planning for the layer, the time to manufacture is directly dependent on the number of layers. If uniform slicing is used, this translates to a direct dependence on the height of the object. However, if adaptive slicing is used, the build direction for minimizing the time may not correspond to the minimum height direction.

(2) The quality of selected surfaces or total surface quality as measured by surface roughness:

- Part orientation determines which faces of the part are most subjected to the

stair-case effect.

- In some processes, contact with the build platform greatly reduces the surface quality on faces that act as the part's base. Poor surface quality, especially on important faces, increases the finishing time and hence the cost of the part.

(3) The area of the base on which the part rests. This area both affects the stability of the part as it is built

(4) The mechanical properties of the part produced. As a consequence of layered manufacture, the parts produced are orthotropic - i.e. the material properties along the build direction are different from those in directions perpendicular to it.

(5) The distortion or curl produced in a part is affected by part orientation. Also, some tolerances on parts are directionally dependent due to differences in coefficients of expansion along different directions

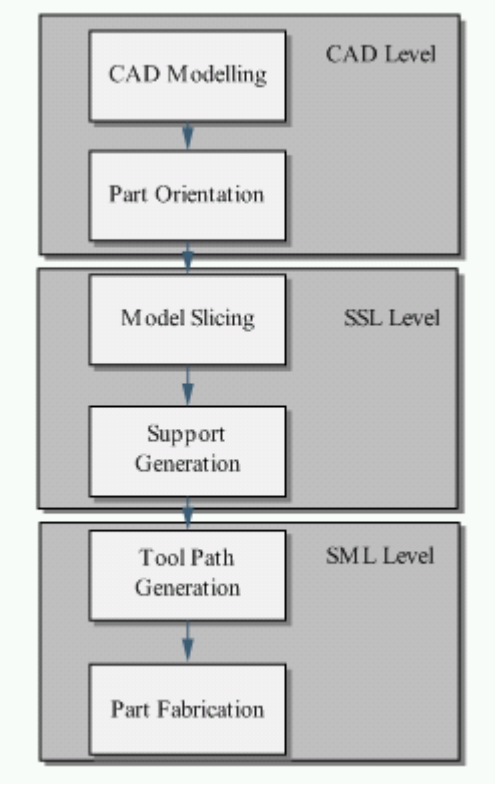


Figure 3.14. Data flow in FDM

In this study, built orientation is determined on the CAD model directly, by user preferences. There is no detail algorithm; the selection of built orientation depends on the user experience, the rules stated above and the part geometry which will build.

3.6.2. Slicing

The growth of RP has created the need for better technology in terms of model representation, accuracy and functionality. Traditionally, RP process involves the conversion of the 3D models into STL format. The procedure worked in the manufacturing industry which used RP to evaluate product designs and aesthetics by producing actual prototypes. However, the geometric description used to represent solid CAD objects significantly affects the accuracy and quality of the final parts produced especially in the case of complex surface formed shapes and the parts which works in assembly. The complexity of the geometry of the parts requires a more direct method in conversion of CAD data to process planning instructions. The process of tessellation and representation in STL format is inadequate for designing complex freeform parts. This is due to the large number of triangles during the conversion process. Direct slicing of CAD models without the intermediate .STL format is preferred because it helps keep the geometric and topological robustness that the original data have and no intermediate conversion process is required.

3.6.2.1. Conventional STL Based Slicing

Slicing is defined as the procedure to convert the CAD model to a layer by layer instruction file set to drive RP systems. The current industry standard of importing CAD models into RP software is through the conversion of the CAD model to a triangular mesh file using an available tessellation algorithm. The triangulation process converts the surface of the CAD model to triangular facets and the tessellated model is then written to the .stl format and then sliced to enable RP machines to fabricate the model.

3.6.2.2. Direct Slicing of IGES Based NURBS Models

Accuracy was not a significant issue in the early days of RP, since the parts could only be used for prototyping and design verification purposes. However, improving the accuracy of an RP part has become the focus of the RP community under the increasing

need for prototyping functional parts with engineering properties and dimensional tolerances comparable to parts produced conventionally (Guduri et all., 1992; Bablani et all., 1995). Direct slicing is an approach that can address this issue, since it seeks to remove the drawbacks of the STL standard. The process involves the direct calculation of the slice contour using the exact mathematic equations used to represent the CAD model (Jamieson, 1995).

The field of direct slicing for RP has been researched on since the middle 1990s. All of the papers published, as discussed in previous sections, depend on external modeling packages to perform the slicing process which in turn limits the capability on the level of control and variety that can be achieved.

Therefore the objective of this section of the thesis is to present a direct slicing approach that is independent of any CAD modeling package and that which makes use of the IGES as the starting input file of the model to be prototyped. We have currently focused on NURBS based parts to demonstrate the capability of the algorithm and the proposed methodology. A point that we would like to stress is that the proposed method in no way replaces the STL based method of indirect slicing which is more suited to traditional manufacturing components and that the use of the direct slicing approach is particularly well suited for parts that have complex geometry which in its STL representation carries drawbacks.

The CAD model is now sliced to generate process plan instructions for the FDM RP machine. The following sections of this thesis will describe the conversion of CAD models to process planning instructions for the RP machine. Although, the conventional method is to first convert the CAD model to an STL based model, our effort is to directly slice the CAD model and transfer the information to the machine eliminating the need for the intermediate file format.

Initially, the CAD IGES file is input into the software framework is implemented to extract out the model geometry. The model geometry in its NURBS representation is then transferred to the slicing module. Each cross sectional layer is then extracted from the model based on the slicing parameters and then converted to machine job instructions.

3.6.2.3. Direct Slicing of NURBS Surfaces Using Ray Casting

Central to the problem of slicing NURBS surfaces is the determination of intersection points between the slicing plane and the model. This problem has been researched by the computer graphics community with regards to ray-tracing of NURBS surfaces (Sweeney et all., 1986; Daniel et all., 1990; Martin et all., 2000; Barth et all., 1993). Ray tracing are commonly used in 3D visualization of models and real time rendering of images.

Ray casting is applied in direct slicing of the CAD models created in the UG system. The basic principle is to fire a parallel beam of rays towards a model and obtain the scan line pattern in a layer by determining the intersections of the rays with the model (Figure 3.15). Instead of performing ray casting for all the layers, the algorithm ensures that only a certain number of layers are involved. The layers which are called ray casting layers are determined according to the geometric features of the model, such as the extreme points on the surface and the required accuracy tolerance. The other aspect of the algorithm is to interpolate the scan line patterns for the layers that are within the ray casting layers. To do that the scan line patterns in the lower and upper ray casting layers and the geometric and topological information that contains in the layers are required.

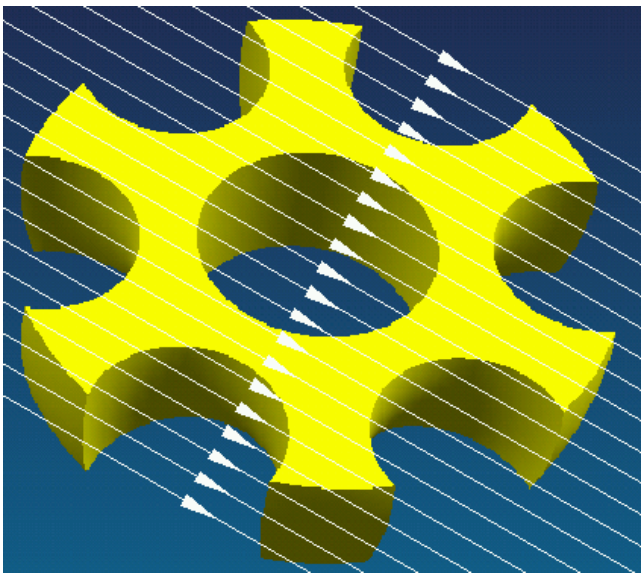


Figure 3.15. Ray casting in direct slicing

At the beginning of the slicing process, the model is divided into a number of regions which are separated by the ray casting layers. For the efficient implementation of the slicing process, the number of ray casting layers been kept to a minimum.

For the proper interpolation of layers within the region bounded by the lower and upper ray casting layers, the two linked list of contour segments that bound the cross sections respectively in the two ray casting layers should be topologically equivalent. Two contour segments are said to be topologically equivalent if they lie on the same face. For the definition of topological equivalency of two lists of contour segments, all individual members in the lists should be topological equivalent correspondingly. The scan line patterns within the region should be within the accuracy tolerance specified by the user.

3.6.2.4. Adaptive Slicing of CAD Model

Most of the problems associated in direct slicing are due to the nature of the fabrication process, and result in an inaccurate finished part. One of the most important problem is the stair-case effect of the finished parts, which is common to all RP techniques.

For controlling the accuracy of the model and for reducing the staircase effect, adaptive slicing needs to be performed. In adaptive slicing procedure, the user can specify a maximum allowable cusp height for the model. Then, the layer thicknesses are computed based on the surface geometry and the predescribed cusp height (Dolenc, 1994; Hope, 1997; Tyberg 1998).

Adaptive slicing has two advantages over uniform slicing. First, the surface quality of the manufactured part is better due to a less staircase effect. Variations in cusp height are minimized, giving the manufactured object a smooth finish. The second advantage of adaptive slicing is a reduction in the build time. The surface geometry has a large impact on the number of slices required to satisfy a specified cusp height.

Since the layers of the physical material must have finite thickness, the stair-case problem is inevitable as shown in figure 3.16. While increasing the number of slices will improve the accuracy, not without extending the fabrication time. Other factors involved in the accuracy of finished parts include CAD data, post processing techniques, machine operation skills, etc.

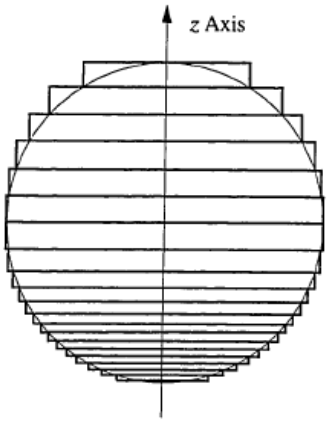


Figure 3.16. Stair-case effect and adaptive solution (After Zhou, 2000)

The building direction on a RP machine is assumed to be in the *z* axis direction of a model and the slicing plane is parallel to the x-y plane. The slice contour is the result of the intersection between the slicing plane and the model surface. The *z* plane at a point on the slice contour is perpendicular to both the slicing plane and the normal direction at that point. The *z* plane intersects the model surface and results in a *z* profile curve. The *z* plane gives a cross sectional view of the model in the building direction, which is convenient for studying the stair-case effect (Figure 3.17.).

If the *z* component of a surface normal is in the positive direction of *z* axis, then the surface normal is defined as positive. Otherwise it is defined as negative. If all normals of a surface patch are positive, the surface is defined as a positive surface. If all normals are negative then the surface is defined as a negative surface (Fig. 3.18a.). The cusp height is defined as the maximum deviation from a part to a model in the normal direction of the *z* profile in *z* plane (Figure 3.18b). The cusp volume is defined as the maximum volume deviation from a part to a model in *z* plane. A cusp is said to have a positive containment, if the part has a larger volume than the model (Figure 3.18c). Otherwise the cusp is said to have a negative containment (Figure 3.18d).

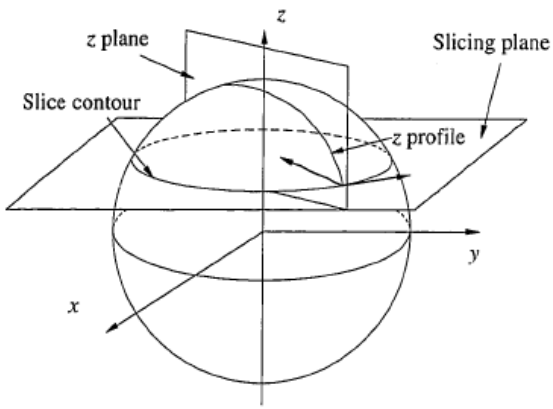


Figure 3.17. Intersection of CAD model with slicing plane

The cusp height is a measurement of the surface roughness which is caused by the stair-case effect of RP fabrication techniques. Difference in cusp height may produce dimensional inaccurate part.

There are generally two techniques for part post processing, i.e., the removal of excessive material and the addition of missing material. Figure 3.18c, d and e show these situations. In Figure 3.18d, the fabricated part has positive cusp containment and a post processing operation is required to remove the excessive material to produce a more accurate part. Similarly, the part shown in Figure 3.18c require the addition of missing material to the part. In the following, three criterions are established for adaptive slicing which take into account of post processing operation:

• **Negative Containment (NC):** The negative containment criteria builds parts in the way such that the cusp volume is always negative, i.e., the part volume is always less than or equal to the model volume.

• **Positive Containment (PC)**: The positive containment criteria builds parts in the way such that the cusp volume is always positive, i.e., the part volume is always larger than or equal to the model volume.

• **Mixed Containment (EC):** The mixed containment criterion builds parts in the way such that the cusp has equal positive and negative volumes.

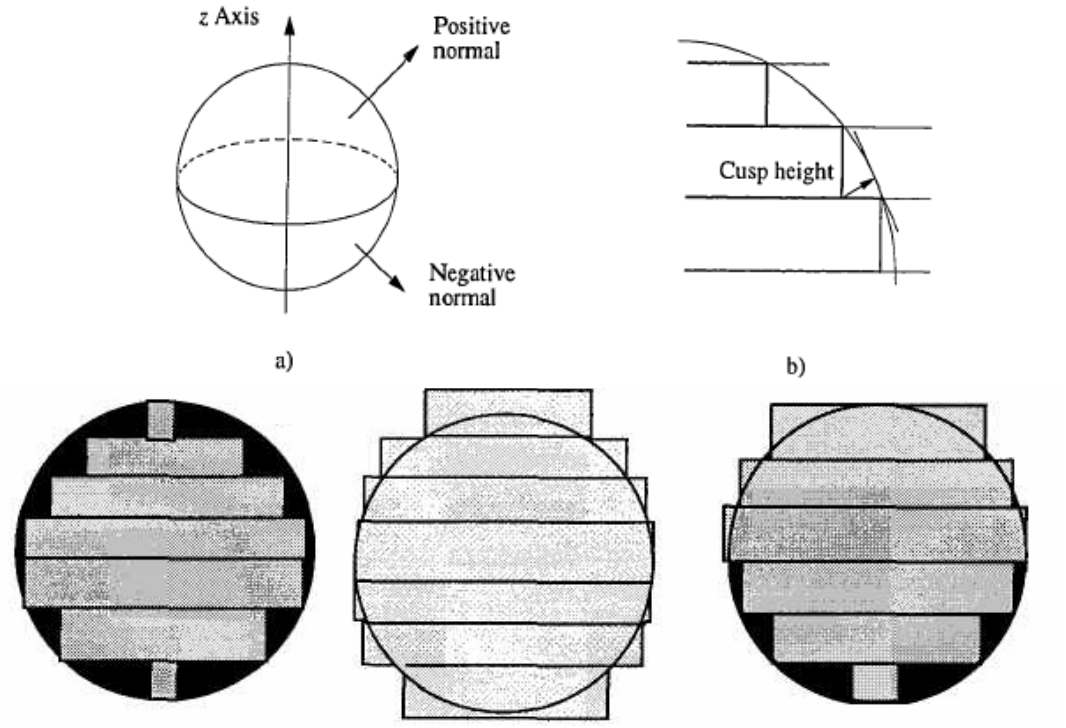


Figure 3.18. Definition of a) surface normal; b)cusp height; c) negative containment; only; (d) positive containment only; and (e) mixed containment (Zhou et all., 2004).

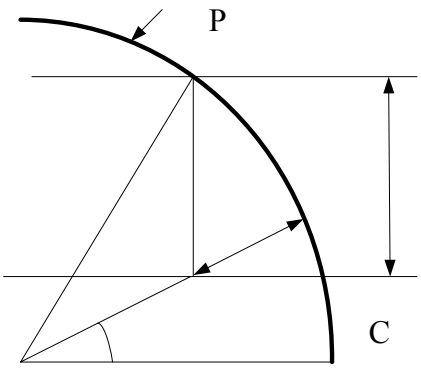
3.6.2.4.(1). Calculation of Layer Thickness

The ultimate goal of adaptive slicing is to selectively slice the CAD model at certain *z* values for efficient and accurate fabrication. The acceptable layer thickness at a point on a surface is often determined by an allowable cusp height and the local surface shape in the vertical direction. The local surface shape in the vertical direction at a point is represented by an intersection curve between the surface itself and a plane passing through the point. The plane normal is determined by a vector product of the surface normal and the z-axis. For determining the layer thickness, the curve is locally approximated with a circle having radius determined by the curvature of the curve at that point, the so called normal curvature in the vertical

direction (Kulkarni, 1996b; Hope et all., 1997a, 1997b, Kumar et all., 2002; Sabourin et all., 1997; Suh et all., 1993).

In RP, the lowest layer is manufactured first and the object is built up on it. The object should either be built up with negative containment or positive containment. Let P be a point on the curve C. The vertical normal curvature of the surface S at the point P is determined. The normal section of the surface at point P is locally approximated as a circle with the radius given by the reciprocal of the absolute value of the vertical curvature at point P as shown in figure 3.19. Using this circular approximation at P, the optimal layer thickness at point P is found based on the deposition requirement and the cusp height requirement on that surface.

The formula for circular approximation depends on whether positive/negative containment is desired, if the curvature is positive/negative, and also if the point P lies in the upper/lower semicircle of the circle of curvature. Thus there are eight possible combinations. For clarity, we group the negative and positive containment situations into two different sections that follow.



where;

N is the surface normal at the point P

θ is the angle that the surface normal makes to the horizontal

ρ is the radius of curvature at P

δ is the allowed cusp height

d is the thickness of the layer

Figure 3.19. Approximation of the local surface curvature (After Tyberg, 1998).

3.6.2.4.(1).a. Negative Containment

We want to derive a formula for d in terms of the other parameters. By applying the law of cosines to the shaded triangle in figure 3.20.;

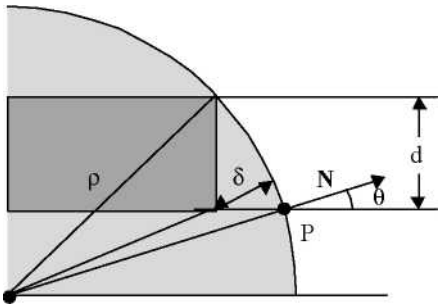


Figure 3.20. Convex curvatures on upper semicircle(After Tyberg, 1998)

$$(\rho - \delta)^2 = \rho^2 + d^2 - 2\rho d \cos(90 - \alpha) \tag{3.22}$$

where (90 - α) is the included angle between sides ρ and *d.*

Using the definition cos(90 - α) = sin α, (3.19) reduces to

$$\rho^2 - 2\rho\delta + \delta^2 = \rho^2 + d^2 - 2\rho d \sin\alpha \tag{3.23}$$

further simplified to obtain

$$d^2 - 2\rho d \sin\alpha + (2\rho\delta - \delta^2 = 0 \tag{3.24}$$

It is clear that

$$\rho \sin\alpha = d + \rho \sin\theta \tag{3.25}$$

By substituting (3.24) into (3.25) and simplifying, it can be shown that

$$d^2 + (2\rho \sin\theta)d - (2\rho\delta - \delta^2) = 0 \tag{3.26}$$

The build layer thickness *d* can now be determined using the quadratic equation:

$$d = \frac{-2\rho\sin\theta + \sqrt{4\rho^2\sin^2\theta + 4(2\rho\delta - \delta^2)}}{2} \tag{3.27}$$

Finally, after simplifying,

$$d = -\rho\sin\theta + \sqrt{\rho^2\sin^2\theta + 2\rho\delta - \delta^2} \tag{3.28}$$

By applying the law of cosines to the shaded triangle in figure 3.21.;

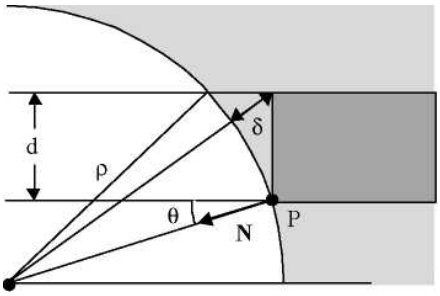


Figure 3.21. Concave curvature on upper semicircle(After Tyberg, 1998)

$$(\rho + \delta)^2 = \rho^2 + d^2 - 2\rho d\cos(90 + \theta) \tag{3.29}$$

where (90 + θ) is the included angle between sides ρ and *d*. Using the definition cos(90 + θ) = -sin θ, (3.26) reduces to

$$\rho^2 + 2\rho\delta + \delta^2 = \rho^2 + d^2 + 2\rho d\sin\theta \tag{3.27}$$

be further simplified to obtain

$$d^2 + (2\rho\sin\theta)d - (2\rho\delta + \delta^2) = 0 \tag{3.30}$$

The build layer thickness *d* can now be determined using the quadratic equation:

$$d = \frac{-2\rho\sin\theta + \sqrt{4\rho^2\sin^2\theta + 4(2\rho\delta + \delta^2)}}{2} \tag{3.31}$$

Finally, after simplifying,

$$d = -\rho\sin\theta + \sqrt{\rho^2\sin^2\theta + 2\rho\delta + \delta^2} \tag{3.32}$$

By applying the law of cosines to the shaded triangle in figure 3.22.;

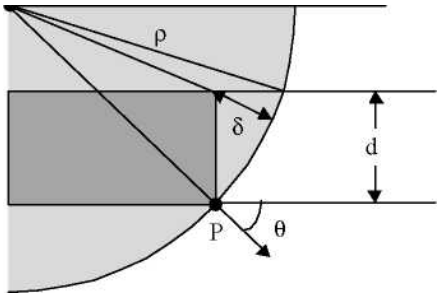


Figure 3.22. Convex Curvature On Lower Semicircle(After Tyberg, 1998)

$$(\rho+\delta)^2 = \rho^2 + d^2 - 2\rho d\cos(90-\theta) \tag{3.33}$$

where (90 -θ) is the included angle between sides ρ and *d*. Using the definition cos(90 - θ) = sin 6, (3.31) reduces to

$$\rho^2 + 2\rho\delta + \delta^2 = \rho^2 + d^2 + 2\rho d\sin\theta \tag{3.34}$$

which can be further simplified to obtain

$$d^2 + (2\rho\sin\theta)d - (2\rho\delta - \delta^2) = 0 \tag{3.35}$$

The build layer thickness *d* can now be determined using the quadratic equation:

$$d = \frac{2\rho\sin\theta + \sqrt{4\rho^2\sin^2\theta - 4(2\rho\delta - \delta^2)}}{2} \tag{3.36}$$

Finally, after simplifying,

$$d = \rho\sin\theta - \sqrt{\rho^2\sin^2\theta - 2\rho\delta - \delta^2} \tag{3.37}$$

By applying the law of cosines to the shaded triangle in figure 3.23.;

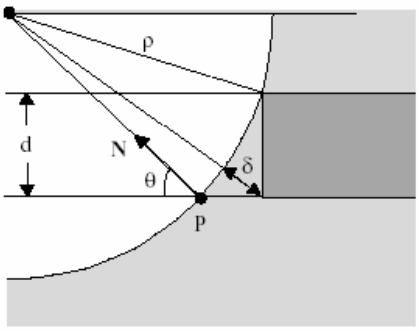


Figure 3.23. Concave Curvature on Lower Semicircle(After Tyberg, 1998)

$$(\rho+\delta)^2 = \rho^2 + d^2 - 2\rho d\cos(90-\alpha) \tag{3.38}$$

where (90 + α) is the included angle between sides ρ and *d*. Using the definition cos(90 + α) = -sin α, (3.36) reduces to

$$\rho^2 + 2\rho\delta + \delta^2 = \rho^2 + d^2 + 2\rho d\sin\alpha \tag{3.39}$$

which can be further simplified to obtain

$$d^2 + 2\rho d\sin\alpha - (2\rho\delta + \delta^2) = 0 \tag{3.40}$$

It is clear that

$$\rho\sin\alpha = -d + \rho\sin\theta \tag{3.41}$$

By substituting (3.40) into (3.41) and simplifying, it can be shown that

$$d^2 - (2\rho\sin\theta)d + (2\rho\delta - \delta^2) = 0 \tag{3.42}$$

The build layer thickness *d* can now be determined using the quadratic equation:

$$d = \frac{2\rho\sin\theta + \sqrt{4\rho^2\sin^2\theta - 4(2\rho\delta - \delta^2)}}{2} \tag{3.43}$$

Finally, after simplifying,

$$d = \rho\sin\theta - \sqrt{\rho^2\sin^2\theta - 2\rho\delta - \delta^2} \tag{3.44}$$

3.6.2.4.(1).b. Positive Containment

As determined before, the formulation for d for the four cases can be derived as:

$$\begin{aligned}
&(i)\ \ d = -\rho\sin\theta + \sqrt{\rho^2\sin^2\theta + 2\rho\delta + \delta^2} \\
&(ii)\ \ d = +\rho\sin\theta - \sqrt{\rho^2\sin^2\theta - 2\rho\delta - \delta^2} \\
&(iii)\ \ d = -\rho\sin\theta + \sqrt{\rho^2\sin^2\theta + 2\rho\delta - \delta^2} \\
&(iv)\ \ d = +\rho\sin\theta - \sqrt{\rho^2\sin^2\theta - 2\rho\delta + \delta^2}
\end{aligned} \tag{3.45}$$

Once again, the expression under the square-root sign can be negative for P in the lower semicircle. Following exactly the same logic, it can be shown that this happens when θ is small implying that the point P is close to the point.

4. RESULTS AND DISCUSSIONS

The research works of this thesis were carried out in the following steps:

- Recognition of IGES files and converting Non-NURBS structures in the IGES files in to the NURBS curves and surfaces,
- Evaluating the maximum dimensions of the part as a bounding box,
- Orient the part,
- Contour recognition and constructing,
- Direct slicing of the part,
- Adaptive direct slicing of the part,
- Compare direct slicing and direct adaptive slicing of parts,
- Creating .SML files of the part to machine in the FDM,
- Developing C++ based OOP Graphical User Interface (GUI) for the part orientation, slicing, path planning and fabrication.

4.1. Programming to Extract NURBS Curves and Surfaces in IGES File

A software tool has been developed in this study to automate the extraction of NURBS geometry data of model from IGES file. OOP approach has been used to develop the software tool.

The types of entity objects to be created to capture the point information depends on the entity types used in the IGES file. The software tool evaluates the entity type at run time and creates the proper object. However, if there exists the class with the interface defined in the package for the types of entities, then the program should be capable of extracting the desired geometric information.

This software explains the development of the formulation to extract the coordinate points from the IGES files of 3D CAD models. Pseudo code of programming is shown in figure 4.1. It also explains the design of the program used to implement the coordinate data extraction formulation. Performance of the program

developed in this study, was tested on three different CAD models. The output of the program is shown as a NURBS curves and surfaces in figures 4.2. and 4.3.

```
& Algorithm to extract the directory entries and the parameter section entries from the
IGES ASCII  file.  This process takes place during the construction of an object of IGES
class. &
Create an empty DirectorySection class (DirectoryEntry objects)
Create an empty ParameterSection class (ParameterEntry objects)
Open the IGES file for reading using IGES ASCII file
& Read IGES file and extract the directory and parameter sections. &
    While ReadLINEARC FirstLine from the IGES ASCII
        If FirstLine belongs to Directory section
            If FirstLine is the first line of DIRectorySECtion of IGES file
                Set DirectoryIndex to 1
            ReadLine Line2 from the IGES ASCII
            Create an object NewDirectoryEntry of class DirectoryEntry
            Set NewDirectoryEntry index using DirectoryIndex
            Initialize NewDirectoryEntry using string FirstLine+Line2
            Add NewDirectoryEntry to DirectorySection class
            Set DirectoryIndex = DirectoryIndex + 1
        If FirstLine belongs to Parameter Section
            If FirstLine is the first line of PARameterSECtion of IGES file
                Set ParameterIndex to 1
            Create an empty string Line2
            while ParameterEntry data incomplete
                ReadLine Line3 from the IGES ASCII
                Append Line3 to Line2
            Create an object NewParameterEntry of class ParameterEntry
            Set NewParameterEntry index equal to ParameterIndex
            Initialize NewParameterEntry using string FirstLine+Line2
            Add NewParameterEntry to ParameterSection class
            Set ParameterIndex = ParameterIndex + 1
        If FirstLine belongs to Terminate Section
        exit while loop
    End of while loop
```

Figure 4.1. Pseudo code of programming

Upper index of Sum

Degree

PROP 1…4 0/1

KNOTS	**WEIGHT**	**CONTROL POINTS**	**UNIT NORMALS**
$\begin{pmatrix} u_0 \\ u_1 \\ . \\ . \\ u_{n+p+1} \end{pmatrix}$	$\begin{pmatrix} w_0 \\ w_1 \\ . \\ . \\ w_n \end{pmatrix}$	$\begin{pmatrix} P_0x & P_0y & P_0z \\ P_1x & P_1y & P_1z \\ . & . & . \\ . & . & . \\ P_Nx & P_Ny & P_Nz \end{pmatrix}$	$\begin{pmatrix} n^x \\ n^y \\ n^z \end{pmatrix}$

Figure 4.2. The output of the program of NURBS curve

Number of Control points in u direction

Number of Control points in v direction

Degree in u direction

Degree in v direction

PROP 1…5 0/1

KNOTS		**WEIGHT**	**CONTROL POINTS**	**UNIT NORMALS**
u direction	**v direction**			
$\begin{pmatrix} u_0 \\ u_1 \\ . \\ . \\ u_m \end{pmatrix}$	$\begin{pmatrix} v_0 \\ v_1 \\ . \\ . \\ v_n \end{pmatrix}$	$\begin{pmatrix} w_{0,0} \\ w_{1,0} \\ . \\ . \\ w_{m,n} \end{pmatrix}$	$\begin{pmatrix} P_{0,0}x & P_{0,0}y & P_{0,0}z \\ P_{1,0}x & P_{1,0}y & P_{1,0}z \\ . & . & . \\ . & . & . \\ P_{M,N}x & P_{M,N}y & P_{M,N}z \end{pmatrix}$	$\begin{pmatrix} n^x \\ n^y \\ n^z \end{pmatrix}$

Figure 4.3. The output of the program of NURBS surface

4.2. Orientation of CAD Model

The model orientation during fabrication of LM part may affect the build time, part strength and surface finish. Thus before the part is sliced, a minimization of

certain objective criteria specified by the designer will be performed to find the optimal orientation for slicing the model. We have used a scheme in which the model is oriented about user specified axes to obtain the least possible build height dimension. Given a set of n NURBS surfaces $S_{t...n}(u,v)$ that is enclosed in a bounding box of height H (a function of orientation angle "θ"), the objective function can be mathematically expressed as:

$$\text{Min } Z = H(\theta) \quad \text{subject to } 0 < \theta < 360 \tag{4.1}$$

where, Z is the build height of the model and θ is the orientation of the model with respect to the object coordinate axes. The optimally oriented NURBS faces with the least height in the z-direction act as the input to the slicing step. Figure 4.4. shows the object entry field for orientation of part in user interface.

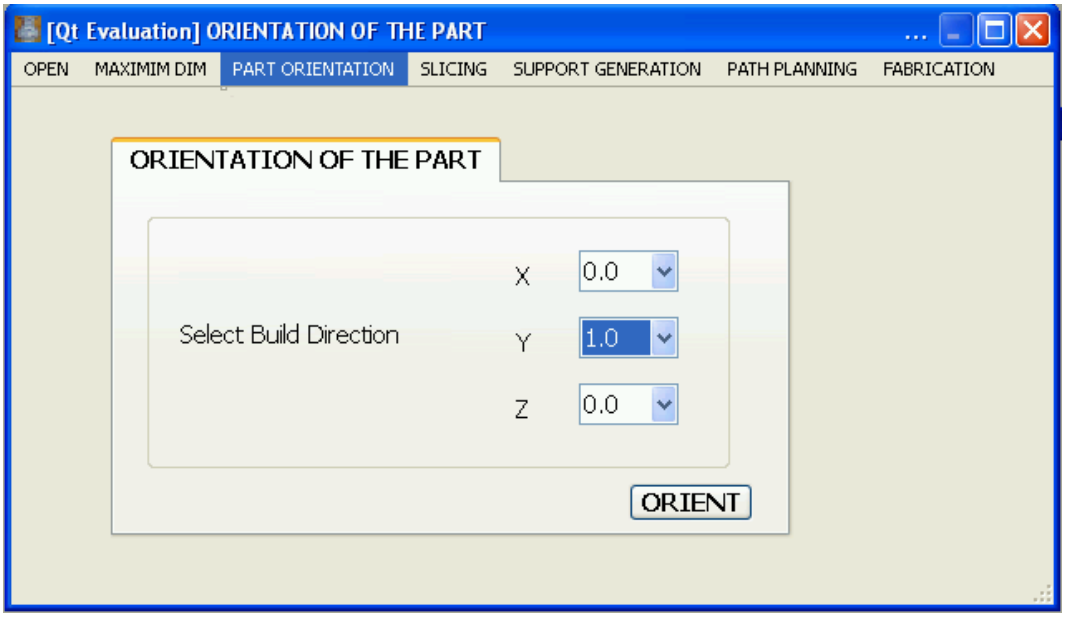


Figure 4.4. Entry field in orientation of the part

For the FDM process, the key objectives would be minimization of support material, minimization of build time, and maximization of surface quality. Since this research does not focus on optimization of orientation, no algorithm is included at this time.

4.3. Slicing

When the model located inside the machine envelope and oriented as desired, slicing function may proceed. Two algorithms are implemented in this study: a uniform and an adaptive slicing algorithm. The uniform slicing algorithm takes as input a slice thickness. Conversely, the adaptive slicing algorithm takes as input minimum and maximum slice thickness value and cusp height. Both algorithms require other process information including machine minimum and maximum layer thickness limits. Checks are performed to ensure that the user-supplied thickness values lie within the system limits.

Software has been written to acquire the NURBS data of the CAD model from the modeling and is output in a predefined text format. This input file is read by the slicing module and the appropriate print path instructions are generated. These instructions in the form of a machine dependant output are read by the software to slice layers that make up the model.

4.3.1. Direct slicing

The purpose of direct slicing in this study is to transfer data directly from a CAD model to a LM system for the building of the model. This slicing method involves the retrieval of cross section profiles for building the layers by intersecting infinite planes with the model. By taking advantage of the CAD modeler's intersection capabilities, the cross section profiles are accurate and complete. The cross section profiles are then converted to the scan lines whose end points are the intersections of the profiles with straight lines (Figure 4.5.).

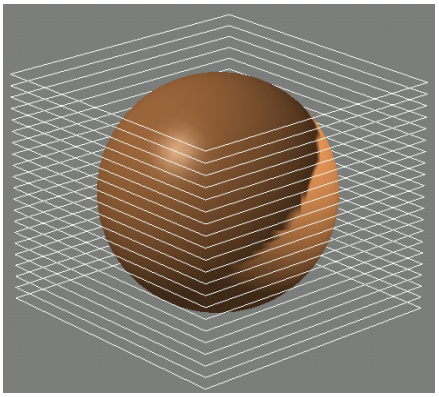


Figure 4.5. Cross section profile by intersecting planes with the model

The extreme points are first detected with all the input data as shown in figure 4.6. The slicing operation will start from the lowest extreme point of the model layer by layer upwards and terminates when reaching the top extreme point. The uniform slicing algorithm begins by inquiring the part bounds on the reoriented model. In this manner, the number of layers can be determined. Datum is created and intersected with each solid body. This produces an intersection feature for each solid body involved. With the slicing plane and the intersection feature created, the slicing loop is entered. The loop contains the individual layer creation operations and is executed once for each layer (Figure 4.7.).

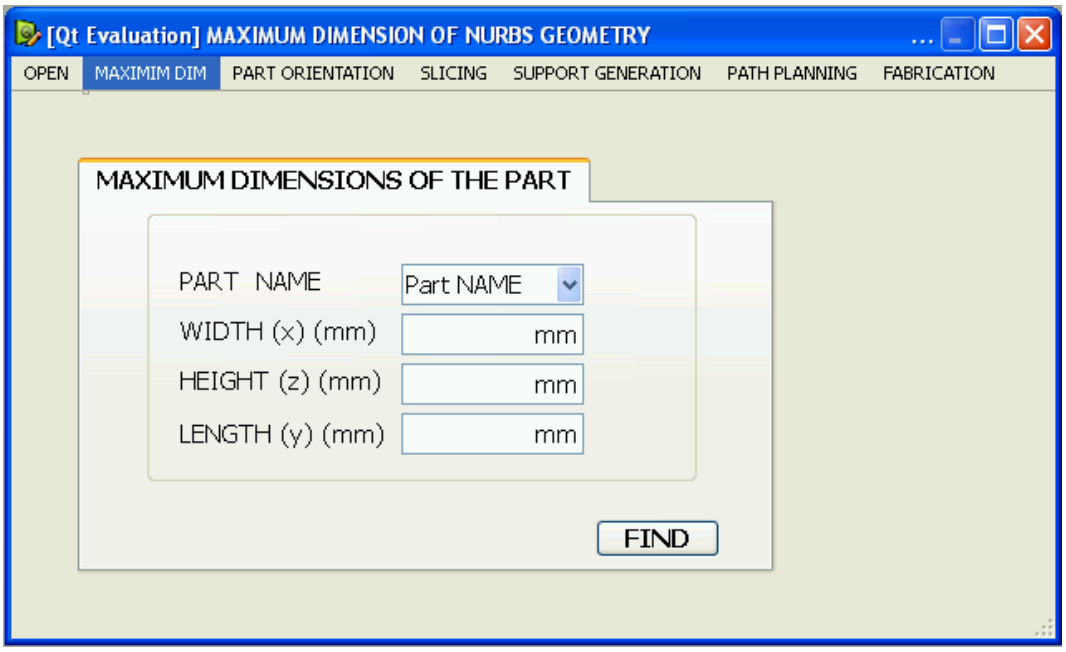


Figure 4.6.The extreme points of the part

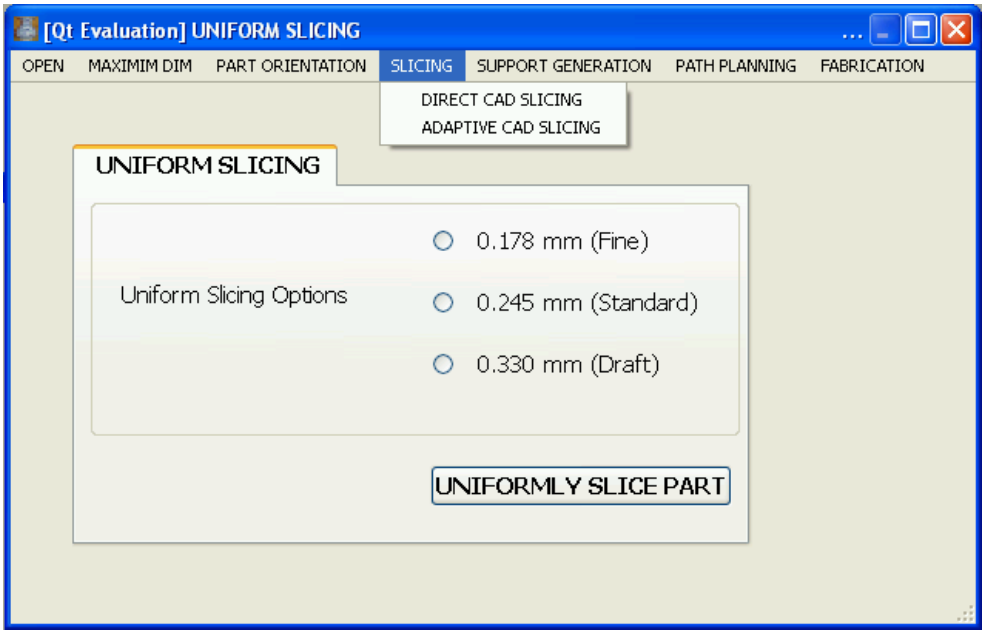


Figure 4.7. The uniform slicing in user interface

4.3.2. Adaptive Slicing

The slicing procedure begins with the selection of model surfaces that form an enclosed volume with appropriate surface normal and slicing parameters. Slicing parameters include cusp heights, minimum and maximum layer thickness as shown in figure 4.8. The slicing operation will start from the lowest extreme point of the model. A horizontal xy plane at the z-height of each layer will intersect with all surfaces and the information of the intersection contours is collected. All contours are further sampled into contour points. The vertical curvature and z-normal at each contour point on the corresponding surface are further determined for calculating the layer thickness. The final layer thickness of this layer is determined according to the layer thickness of all contour points, extreme points of the model, minimum and maximum layer thickness of the RP system. Contour coordinates are calculated based on the final layer thickness and other input parameters. The slicing procedure will iterate for the following layers until the last layer at the highest extreme point is sliced.

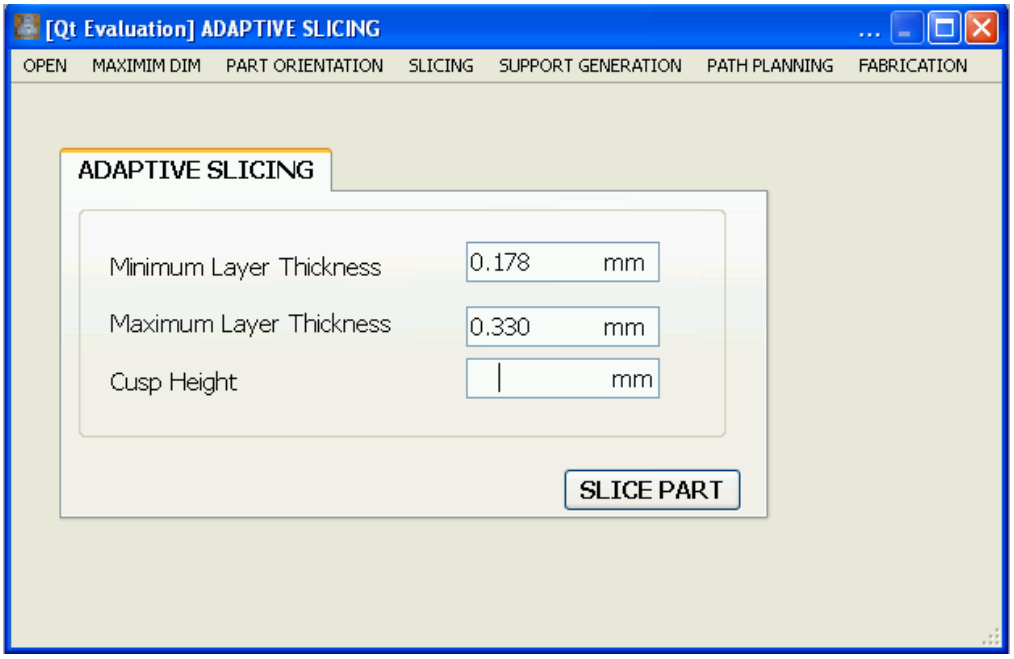


Figure 4.8. Adaptive slicing and slicing parameters

After slicing, the results and related parameters, including the total number of adaptive layers, positive and negative cusp height, minimum and maximum layer thickness and extreme point information are saved in a file for further processing. Figure 4.9. shows flowchart for adaptive slicing used in this work.

4.4. Build Strategies and Fabrication

Geometric description of the object at each layer consists of closed contours, as shown in figure 4.10. for a vase. Object contours can further be classified based on their visibility properties from top and bottom. Due to dynamics of road deposition, flat bottom facing layers need to be constructed with carefully determined flow parameters to ensure acceptable levels of surface roughness. Bottom facing flat surfaces would be invariably supported by support material and process parameters would be required to ensure acceptable surface quality. Similarly, flat top facing layers and a few layers under the flat layer would be produced with well calibrated deposition parameters to avoid excess deposition material or sinks on the flat surface.

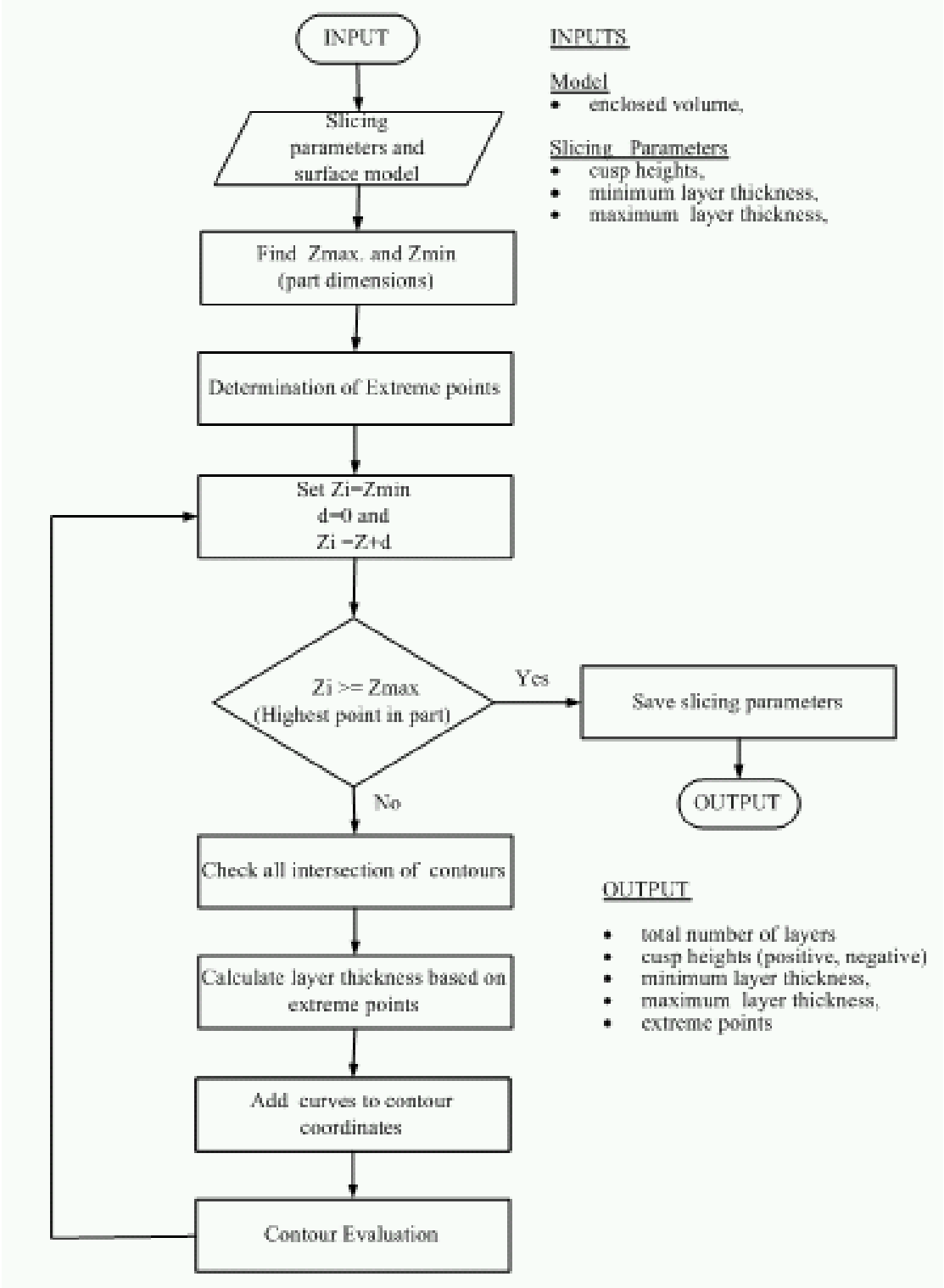
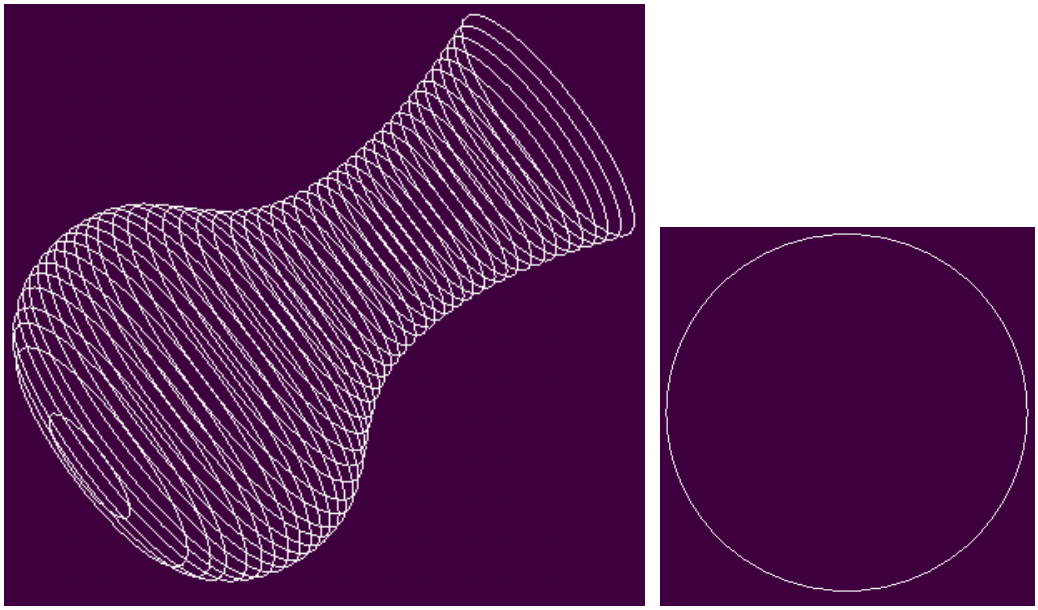


Figure 4.9. Flow chart for adaptive slicing



(a) (b)

Figure 4.10. Slice Description for vase (a); all contour, (b); contour number of 34

Small angle overhangs from vertical wall are allowed in support structure determination, as deposited roads are able to support a certain amount of overhang. In the immediate vicinity of the part, a tight support structure is generated for better part surface finish and ease of support structure removal. Rest of the support volume is designated to be built with coarser structures to minimize material consumption and build time without compromising part stability during the process. The part can be supported at portions where it is needed, direct supports; or can be contained into a box of support structures, containment supports. Direct supports, consume minimal amount of material and result in faster build times; on the other hand containment supports would isolate the part from the variability of the build environment and result in higher quality parts (figure 4.11.)

For the FDM process, the key objectives are the minimization of support material, minimization of build time and maximization of surface quality. Since this research does not focus on support structure generation, no algorithm is included at this time.

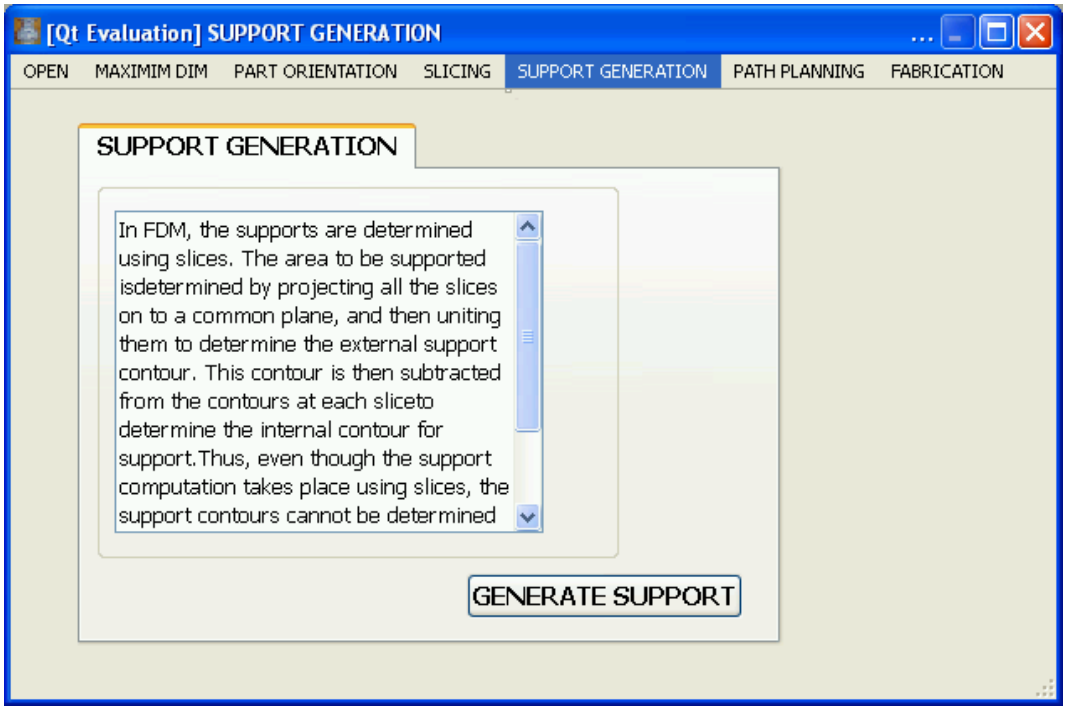


Figure 4.11. Support structure generation

In part deposition system, a foam base is utilized to provide anchor point for the part being produced. Down-facing surfaces on first few layers would have specifically coarse surface textures, due to porosity of foam material. Hence, it has been a common practice to generate five to ten layer base structures out of support material prior to object deposition. The base provides a horizontal build platform, which results finer surface finish on the bottom layers of the object; and thermal isolation from foam material. Geometrically base structure is also defined at the slice level. Base will consist of five to ten identical layers.

Generated slice level information is stored in an ASCII slice file, SSL file. SSL files contain three distinct sections as shown in figure 4.12. The header section contains information about the version of slice format, location of the generated file; type of the intended modeler, material pair, tip and layer thickness; and location of the relevant configuration files. The configuration files, DEF files, are utilized along with the SSL file to generate tool-path and flow control commands by the process planning.

Header

Slice format and Software Version
File generation Date
Type of File
Modeler Type
Material Types
Tip Type
Path of Relevant DEF Files
Units
Layer Thickness
Shrinkage Parameters
Tolerances
Tip Cleaning Parameters

Contour Types

For each contour type
    ID, Name, Tool-Path Type, Raster Angle, Road Width,
    Air Gaps, Deposition Speed, Appearance Colour,
    Flow Control Commands.

Geometry

For each Layer
    Z-coordinate and slice thickness
    For each contour in layer
        Contour type
        Number of points in contour
        Point Coordinates
End layer Loop
END

Figure 4.12. SSL file structure

The second section within the file contains description of contour types utilized in the file. Each type is uniquely defined with an identification number and stored in data-structure entities named groups. The group data-structure includes two types of information: representational properties of the group for ease of identification within the process planning software, such as a designated name and drawing color and tool-path generation properties; such as presence of perimeter/contour/raster/open roads; road width, raster angle, deposition speed and flow control commands for each road; and air-gaps between and within road types.

In the final section of the slice file, contours are described as closed contour arranged into layered structures. Start of each layer is marked by a line stating the layer elevation and thickness. For each contour in the layer, contour identification

number is specified followed by the number of points on the particular contour. Planar coordinates of contour points are specified in proper orientation. The seven character header in the trailer line specifies the kind of contour that has been specified and the six numbers that follow the header specify bounding box of the contour perimeter and signed area. On the other hand if all contours in the layer have been specified, layer trailing follows. The layer trailing section consists of lines only with the character '*', and numbered as many times as the number of contours within the layer. Finally, the geometric description of the part is ended with a part trailer "END".

FDM systems extrude and deposit molten material from a liquefier head with a nozzle attached to it. The process of deposition in each layer starts with a road of material of defined width and thickness being deposited to define the perimeter(s) or boundary (ies) of the given part layer. Each perimeter or boundary is a closed loop with a start and end point. Once the perimeters are defined, the internal portion of the layer is filled by roads of defined width and thickness in one of three ways (see Figure 4.13.):

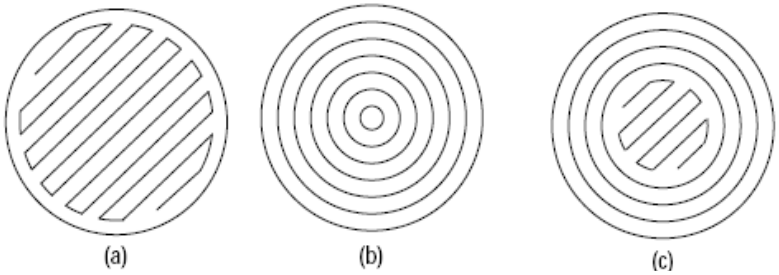


Figure 4.13. Build Strategies in FDM: (a) raster pattern, (b) contour pattern, (c) contour/raster pattern (Stratasys, 2006)

(1) Raster based methods: Raster tool-paths are open contour that are generated from parallel lines deployed into the structure at pre-specified angles. Parallel lines are generated based on the bounding curves using ray-casting methods. Subsequently, generated parallel lines are joined at ends to form maximum length continuous tool-paths.

(2) Contour based methods: Each layer generally has at least one contour based tool-path, namely the closed contour defining the perimeter. Additional tool-

paths are generated with curve offsetting techniques using the road-width and air gap settings for the particular curve.

(3) Contour and raster fill: A combination of the first two approaches such that the deposition of the region, defined by the perimeter, is followed by deposition of material by a few contour motion followed by raster filling of rest of the internal area.

The raster fill approach is used most frequently due to its speed and the ability to change the direction of raster motion in adjacent layers. Typically, alternate layers are built with raster directions at 90° to one another. Such a strategy results in maximum packing of material and a minimum of voids between roads and layers. Depending on the complexity of a given closed loop feature in a layer, there may be more than one raster segment.

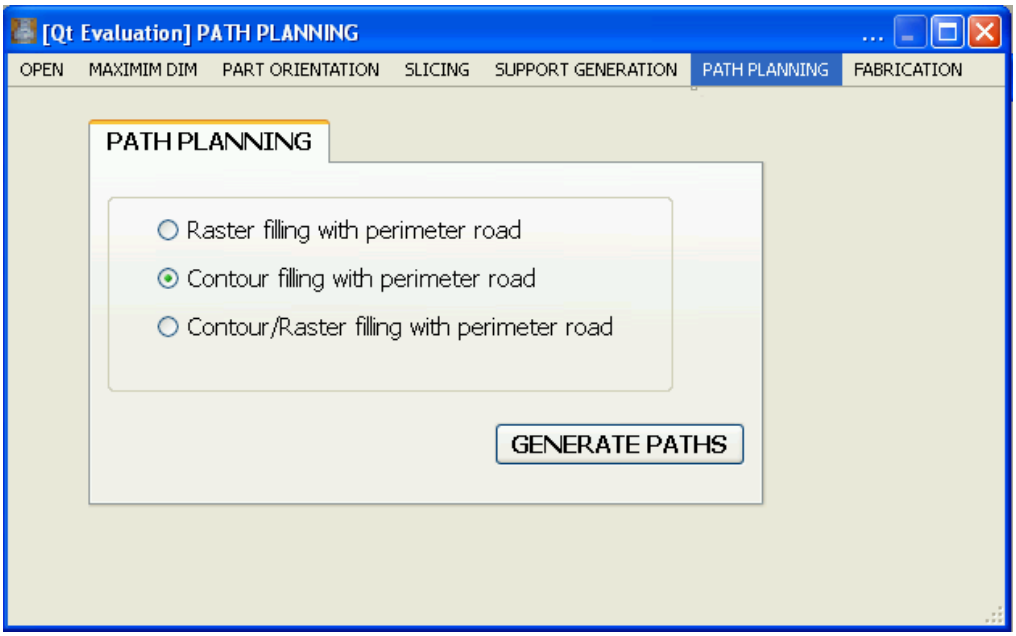


Figure 4.14. Generation of paths in FDM

In addition to road width, thickness, liquefier head speed and fill pattern, several other build parameters require optimization for a given material system for defect-free FDM processing. Most of these parameters have to do with material flow and liquefier head motion at the beginning and end of a given segment, whether the segment is a closed loop perimeter or a raster segment. Poor optimization of material flow and

liquefier head motion parameters at the beginning and end of a perimeter or raster segment can result in defects detrimental to structural properties of the parts.

Tool-path geometry and associated flow control parameters need to be transferred to the FDM hardware in a sequential fashion. The standard language of the controller has been extended through incorporation of an 8-bit interface for flow control purposes and was renamed as Stratasys Modeling Language (SML). Tool-path and flow control related commands and parameters are stored in an ASCII SML file and relayed to the hardware through standard RS232 connection. Figure 4.15. shows the modeler selection and creating .SML files in user interface.

Hardware initialization commands enable the modeler to locate the origin of coordinate system. The machine operation is paused to allow the placement of the deposition tip onto the building foam by the user; and initialization sequence is continued through material purge and subsequent extrusion tip wipes. User intervention for nozzle placement is cumbersome and slows down execution of the process. In hardware architecture, flow control commands are relayed to the controller through motion controller interface, which is in SML language.

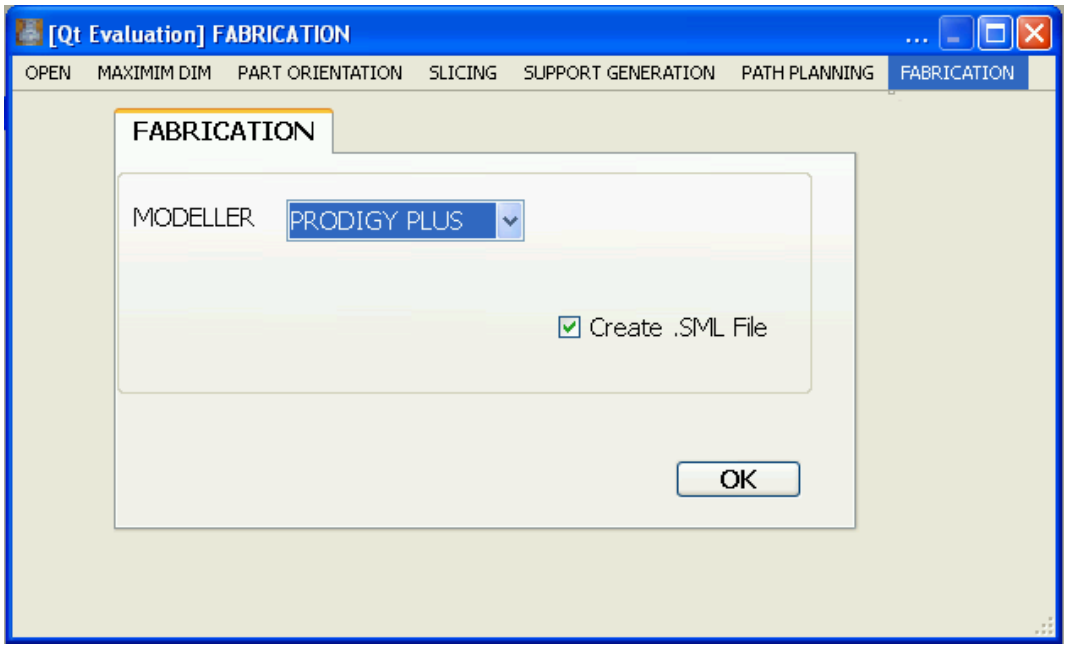


Figure 4.15. Creating .SML file FDM Modeller

4.5. Model Case Studies

The developed algorithm was tested for 4 different models each with certain characteristics. The first two sphere, as shown in figure 4.16., and vase, as shown in figure 4.17., which are literature dependent the other two rotor, as shown in figure 4.18., and ring star, as shown in figure 4.19., which are industrial part in assembled form. All the parts are modeled in UG environment as a surface model and saved as IGES format. The necessary information in IGES files are transformed in to NURBS curve and surface structure.

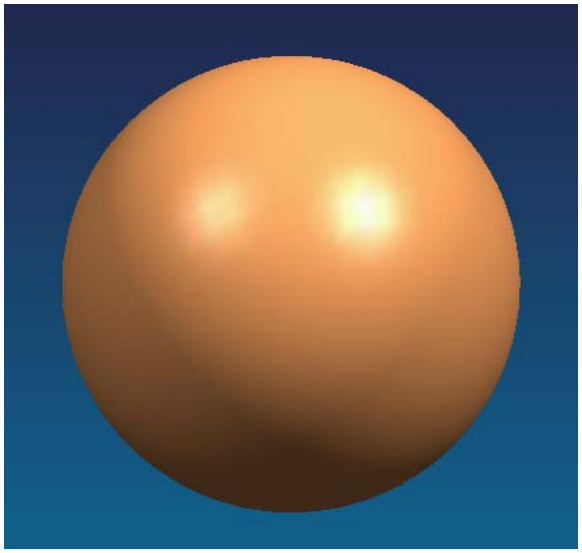
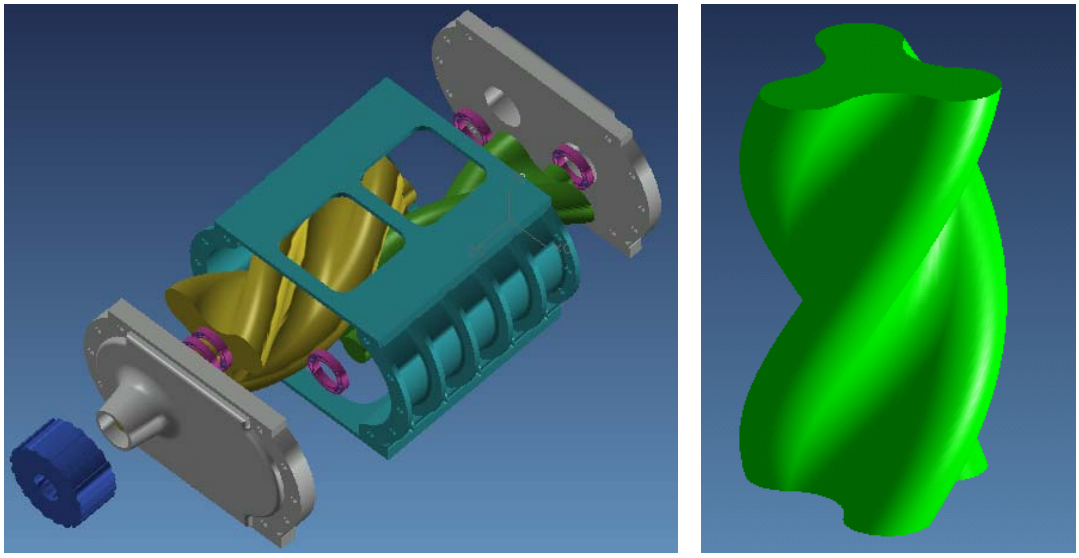


Figure 4.16. Sphere modeled in UG

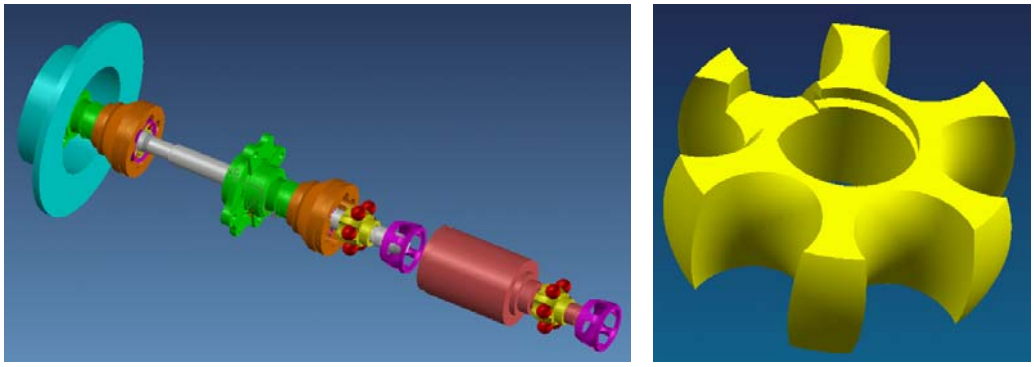


Figure 4.17. Vase modeled in UG



(a) (b)

Figure 4.18. (a) Pump assembly with rotor and (b) rotor



(a) (b)

Figure 4.19. (a) Automotive drive assembly with star ring; (b) star ring

4.5.1. Sphere

Direct slicing of sphere is implemented with layer thickness of 0,178 mm (fine), 0,245 mm (standard) and 0, 33 mm (draft). Figure 4.20 shows direct slicing of sphere and table 4.1. shows the changes in number of layers with layer thicknesses.

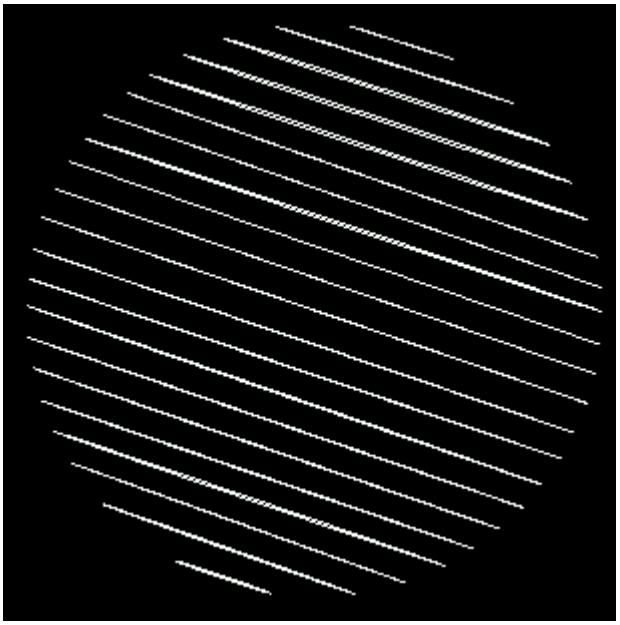


Figure 4.20. Direct slicing of sphere

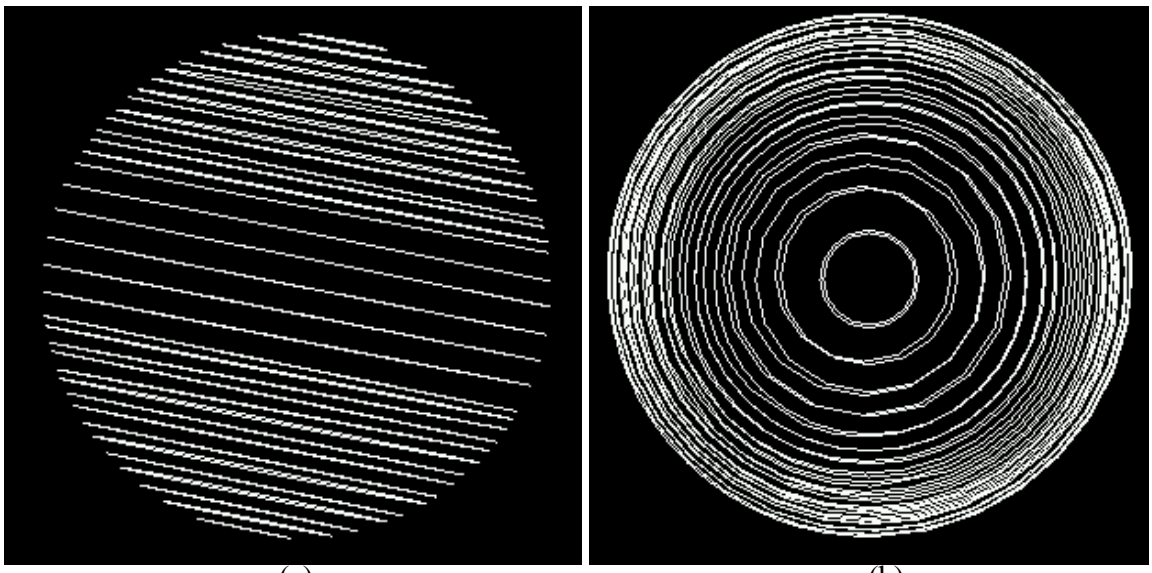
Table 4.1. Changes in number of layers with layer thicknesses for 30mm sphere

Slice Thickness	Number of layers
0,178	187
0,245	135
0,33	99

As shown in table 4.1., when slicing the sphere using the slice thickness of 0,178 mm number of layers is 187, while in 0,33 mm layer thickness, the number of slice is 99. If we increase slice thickness for a whole part, the number of layers decreases that is built time/cost also decreases, but the surface quality is poor. If we decrease the slice thickness, the number of layers increases that is built time/cost also increases, but the surface quality is in acceptable quality. So, we have to compromise the situation where minimum built time/cost and surface quality.

Adaptive slicing of sphere is implemented with minimum layer thickness of 0,178 and maximum layer thickness of 0,33 mm. Sphere is divided in to three or four sub layers according to the containment situation. Then, each sub layer is also further sliced according to their accuracy. Cusp height is also constrained to 0,005, 0,1 and

0,12. Figure 4.21 shows adaptive direct slicing of sphere whit different cusp heights and table 4.2. shows the changes in number of layers with layer thicknesses.



(a) (b)

Figure 4.21 Adaptive slicing of sphere whit different cusp heights (a) front view; (b) top view

Table 4.2. Changes in number of layers with cusp heights for adaptive slicing

Cusp Height	Number of layers
0,005	159
0,1	146
0,12	139

As the table 4.2. shows, when the cusp height 0,005, the number of layers from adaptive slicing is 159 and that of uniform slicing is 187, 135 and 99 for different layer thickness. When the cusp height 0,1, the number of layers from adaptive slicing is 146 and when the cusp height 0,12, the number of layers from adaptive slicing is 137. As can be recognized from the results, adaptive slicing significantly reduces the number of layers, while keeping cusp height in specified tolerances. In evaluating adaptive slicing methods, the cusp height is the most important parameter. Layer thickness adaptively changes according to the surface curvature. So, when the curvature gets steeper, layer thickness gets thicker and layer thickness gets thinner as the curvature gets flat as shown the top and the bottom of

the sphere. Considering the number of slices which strongly effects the building time/cost and part accuracy, adaptive slicing method is more effective than uniform slicing method for curved parts.

4.5.2. Vase

Direct slicing of vase is implemented with layer thickness of 0,178, 0,245 and 0, 33 mm. Figure 4.22 shows direct slicing of vase and table 4.3. shows the changes in number of layers with layer thicknesses.

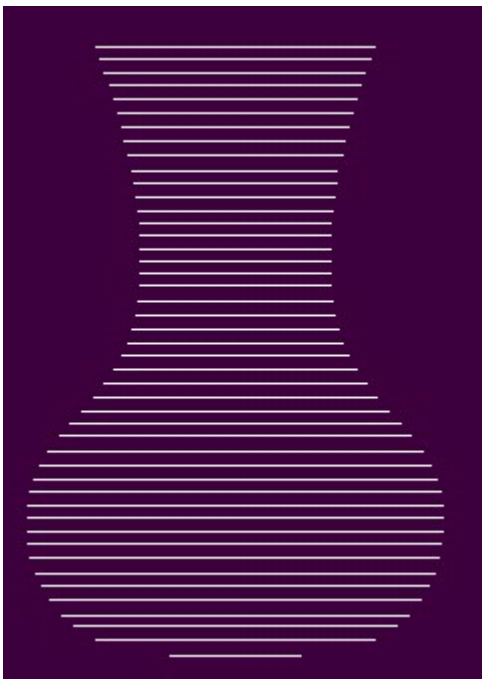


Figure 4.22. Direct slicing of vase

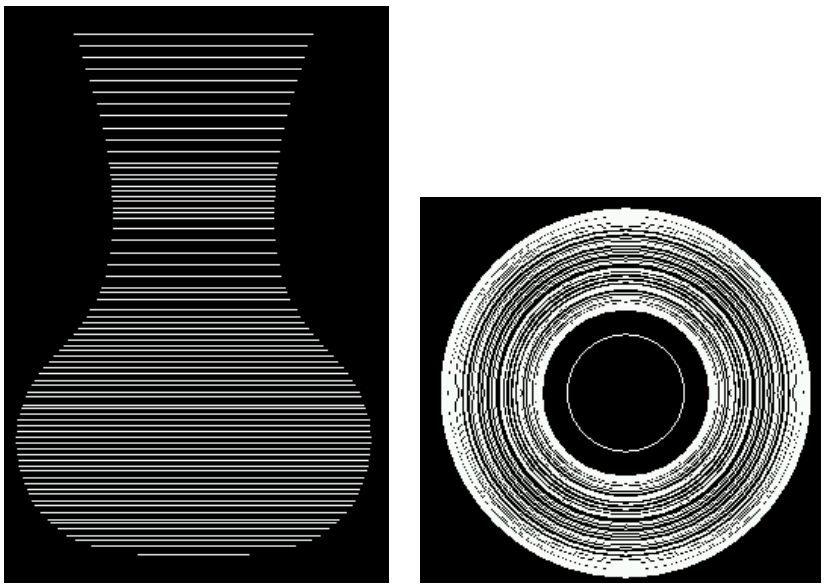
Table 4.3. Changes in number of layers with layer thicknesses for vase

Slice Thickness	Number of layers
0,178	352
0,245	257
0,33	194

As shown in table 4.3., when slicing the sphere using the slice thicknesses of 0,178 mm, 0,245, and 0, 33 mm layer thickness, the numbers of slice are 352, 257 and 194. As in the case of sphere, if we increase slice thickness, the number of layers, built

time/cost decreases, but the surface quality is poor. If we decrease the slice thickness, the number of layers increases, built time/cost increases, but the surface quality is in acceptable quality.

Adaptive slicing of vase is implemented with minimum layer thickness of 0,178 and maximum layer thickness of 0,33 mm. the vase is divided in to six sub layers according to the containment situation. Then, each sub layer is also further sliced according to their accuracy. Cusp height is also constrained to 0,005, 0, 1 and 0,12. Figure 4.23. shows adaptive direct slicing of sphere whit different cusp heights and table 4.4. shows the changes in number of layers with layer thicknesses.



(a) (b)

Figure 4.23. Adaptive slicing of vase whit different cusp heights, (a) front view; (b) top view

Table 4.4. Changes in number of layers with cusp heights for adaptive slicing

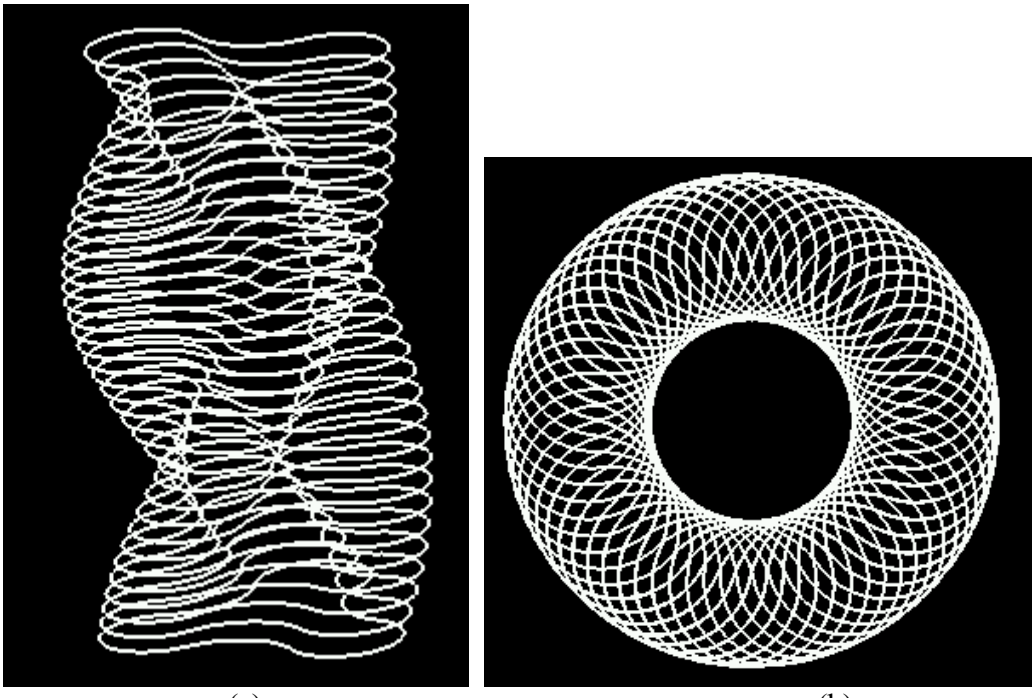
Cusp Height	Number of layers
0,005	296
0,1	259
0,12	234

When the cusp height is 0,1 mm, there is not much difference between the number of slices and the uniform slicing of thickness 0,245 mm. The layer thickness

adaptively changes to the regions where the curvature variation is relatively smaller. As a result, at the middle height of the vase and the highest points of the neck, the layer thickness gets thicker based to the curvature changes. At the bottom of the vase, the layer thickness gets thinner, because maximum curvature variations occur at that region.

4.5.3. Rotor

Direct slicing of rotor, is an industrial part which works in assembly, is implemented with layer thickness of 0,178, 0,245 and 0, 33 mm. Figure 4.24 shows direct slicing of rotor and table 4.5. shows the changes in number of layers with layer thicknesses.



(a) (b)

Figure 4.24. Direct slicing of rotor, (a) isometric view; (b) top view

Table 4. 5. Changes in number of layers with layer thicknesses for rotor

Slice Thickness	Number of layers
0,178	270
0,245	197
0,33	145

In assembly of rotor, as shown in figure 4.23., two rotor are working together. So, surface quality of the parts is more important. As shown in table 4.5., the higher number of slices of 236 is acceptable result for rotor part.

Adaptive slicing of rotor is implemented with minimum layer thickness of 0,178 and maximum layer thickness of 0, 33 mm. The rotor is divided in to five sub layers according to the containment situation. Then, each sub layer is also further sliced according to their accuracy. Cusp height is also constrained to 0,005, 0,1 and 0,12. Figure 4.25. shows adaptive slicing of rotor whit different cusp heights and table 4.6. shows the changes in number of layers with layer thicknesses.

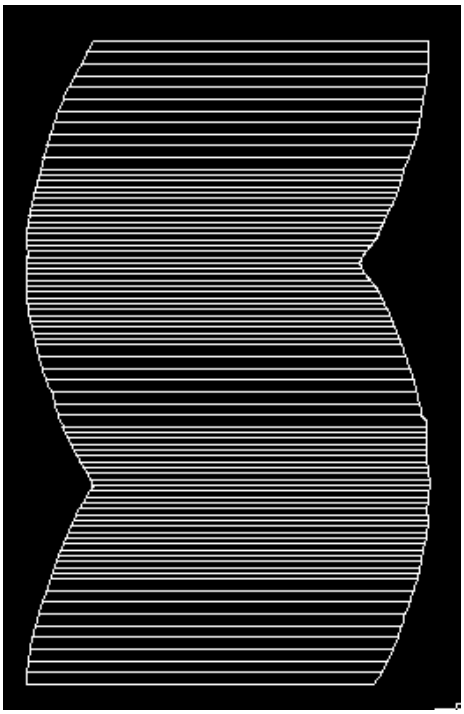


Figure 4.25. Adaptive slicing of rotor

Table 4.6. Changes in number of layers for adaptive slicing of rotor

Cusp Height	Number of layers
0,005	231
0,1	201
0,12	188

As shown in figure 4.25., the layer thickness adaptively changes to the regions where the curvature variation is maximum. As a result, at the first and second

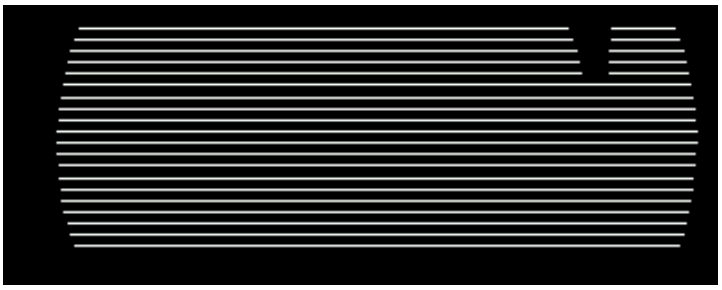
neck of the rotor, the layer thickness gets thinner based on the maximum curvature changes. At the bottom and end of the rotor the layer thickness gets thicker.

4.5.4. Star Ring

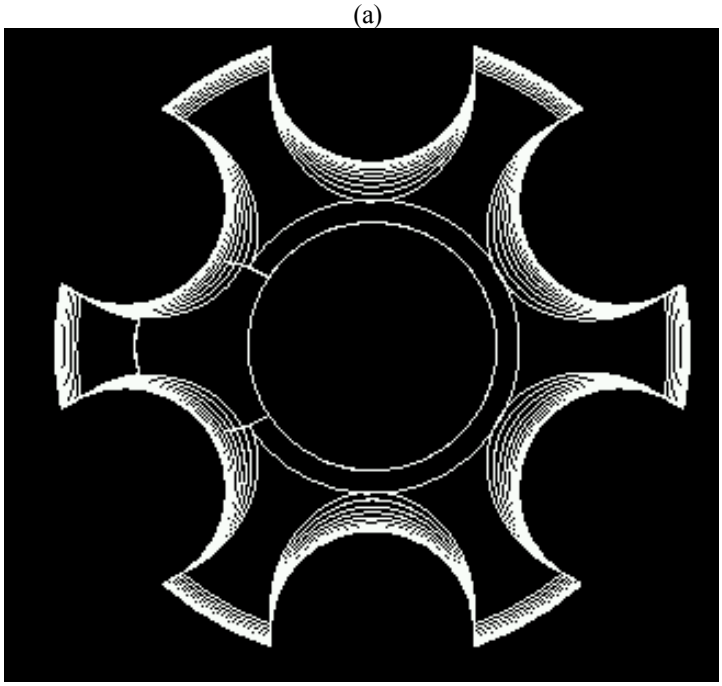
Direct slicing of star ring, which is industrial part is implemented with layer thickness of 0,178, 0,245 and 0, 33 mm. Figure 4.26 shows direct slicing of star ring and table 4.7. shows the changes in number of layers with layer thicknesses.

Table 4. 7. Changes in number of layers with layer thicknesses for star ring

Slice Thickness	Number of layers
0,178	298
0,245	217
0,33	160



(a)



(b)

Figure 4.26. Direct slicing of star ring, (a) front view; (b) top

Adaptive slicing of star ring is implemented with minimum layer thickness of 0,178 and maximum layer thickness of 0,33 mm. the star ring is divided in to four sub layers according to the containment situation. Then, each sub layer is also further sliced according to their accuracy. Cusp height is also constrained to 0,005, 0,1 and 0,12. Figure 4.27. shows adaptive direct slicing of star ring whit different cusp heights and table 4.8. shows the changes in number of layers with layer thicknesses.

Table 4.8. Changes in number of layers for adaptive slicing of star ring

Cusp Height	Number of layers
0,005	265
0,1	239
0,12	221

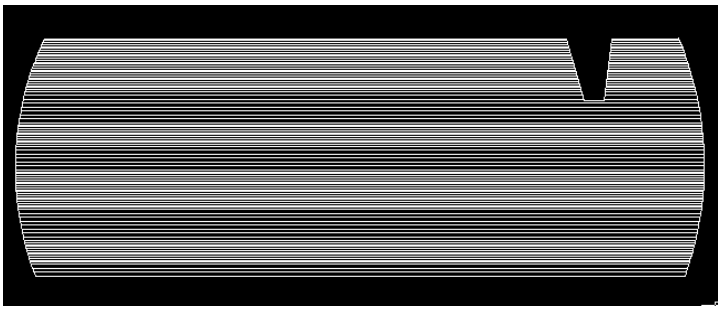


Figure 4.27. Adaptive slicing of star ring

5. CONCLUSION AND FUTURE STUDIES

5.1. Conclusion

The main objective of this research is to develop philosophy, strategies and algorithms for IGES based NURBS models in FDM process. In order to achieve this, the following is developed:

1. Recognition of IGES files and converting Non-NURBS structures in the IGES files in to the NURBS curves and surfaces,
2. The creation of 3D slices to replace the commonly used 2D slices,
3. Direct slicing from the CAD method to avoid inevitable errors which exist in STL file format,
4. The adaptive slicing model to evaluate the performance of process parameters of RP system,
5. C++ based Graphical User Interface (GUI) for the part orientation, slicing, path planning and fabrication.

This research has achieved its objectives and illustrated its potential to cost effectively improve the surface quality of parts built by the FDM process. Direct CAD and adaptive slicing method has been developed and verified. The NURBS based CAD models has been tested and has been shown to provide accurate slice data for uniformly and adaptively.

The CAD model is sliced directly outside CAD modeller so that the slicing process does not rely on a specific CAD modeller. Furthermore, the user can reorientate the part conveniently before slicing. Adaptive direct slicing that we proposed uses variable layer thickness to slice a CAD model directly, considering not only the local geometrical information in the build direction but also different quality requirements for various part surfaces. In layer thickness computation, two important issues which are staircase effect and material containment, which impact the surface quality of the part, are considered simultaneously. Compared to common adaptive slicing and uniform slicing, this process decreases number of layers and building

time of the part and improves surface quality of the part. It has greater slicing efficiency than common adaptive slicing.

This research proposed and then developed and implemented an approach to efficiently improve the surface quality of parts built by a Rapid Prototyping (RP) process, specifically FDM process. The previous research has addressed, with different degrees of success, many issues related to the improvement of part quality, reduction of cost, tradeoffs between quality and cost and the implementations of adaptive slicing. The focus of this research has been to improve the speed of a RP system without sacrificing the quality of the parts produced.

All of the methodologies developed and implemented in this research can be processed offline, and thus neither interferes with the machine performance nor adversely affects its utilization. Usually, the actual machine building process is much longer than the slicing process. Therefore, the increase in pre-processing time will not affect the overall machine performance.

The results of this research provide significant contributions to research in rapid prototyping. However, rapid prototyping research is still at an early stage and there exist many other opportunities to further advance the RP technology. The methodologies developed in this dissertation are believed to provide a good set of tools for carrying out some fundamental research in RP.

The potential advantage that can be realized by this study is benefical to the rapid prototyping industry. In particular, users of FDM systems may benefit from great savings in fabrication time. The potential for savings is directly proportional to the number of individual parts and/or part features in a given build and their respective differences in geometry. Hence, this method is ideal for users in industry who typically optimize fabrication by building multiple parts simultaneously.

5.2. Future Studies

In this research, direct and adaptive slicing method was considered for accurate and faster building process. Recommendation for future work is the calculation of correct building time. Since one of the main usage of rapid

prototyping technology is to reduce development cycle through fast visualization of CAD model. Therefore, correct estimation of building time enhances the concept of rapid prototyping through effective job scheduling based on the estimation time. And through the study of building time, the effect of the parameters could also be investigated.

Due to time and cost limitations, the number of experiments in this research was not generated. The cost of each experiment exceeded $100 and build time for each part ranged from 8 to 24 hours. For future research, it is recommended to test the sample size. This will increase the accuracy of the algorithm and the ability to generalize to new configuration settings within the regions of search space not explored with this research.

Development of new configurations for the FDM system is needed. The model can be used to create good candidates for new machine configurations. Furthermore, if an RP process allows the user to select the parameters over a continuous range, the developed system can reach its goal of optimizing the RP process. Adaptive control techniques have long been utilized for machining processes in which the real-time feedback from the process/work interaction controls the setting for machining parameters. The effects of the model developed in this research will be substantially enhanced if integrated in an adaptive control environment.

Most of the methodologies and algorithms implemented in this research are generic and could be adapted to other RP processes with minor modifications. One of the future research efforts could be the development of similar systems for other RP processes.

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CURRICULUM VITAE

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A.1. RP systems

Rapid prototyping techniques can be classified in two ways according to the way material is created and to the way the shape is built (Jacobs, 1992; Chua et all., 1998). The first classification, material classification, can be subdivided into three different states following the raw material applied: Powder, liquid and solid. In the case of using powder as raw material, the grains are bound by melting together the interfacial grain contact area of a one component powder or by gluing the grain together by selectively adding a binder. Another case of using a solid material as raw material, mostly in the form of thin foils, this process glues or welds foils on top of each other in order to produce the required shape. Finally, many of the present processes adopt the techniques which deposit the raw material in liquid state. In this case, some process uses metals or plastics as base material which is deposited by melting and solidification and another case use the liquid polymer as base material which is solidified by the impact of light from lamps or lasers (Figure A.1).

A.1.1. Stereo Lithography (SLA)

SLA was invented by Charle Hull of 3D Systems Inc (3D System). It is the first commercially available LM system and is considered as the most widely used. The main feature of SLA is reported in table A.1. and working principle is shown in figure A.2.

The advantages of SLA models are their accuracy, detail and surface finish. It is the best known and most popular method for rapid prototyping. They are very useful for checking 3D model integrity, form & fit checking. Applications for SLA models include product design in all industries, medical research and demonstration, automotive and aeronautic development.

The disadvantage of SLA models is that they are relatively brittle which means they are limited for mechanical testing. In order to get a useful test model, it is normally necessary to use the SLA model as a master for creating a vacuum casting tool. Once this tool is created it is possible to get a number of vacuum cast parts in a

stronger, tougher polymer. Over the years, a wide range of materials with properties mimicking those of several engineering thermoplastics have been developed. Limited selectively color changing materials for biomedical and other applications are available and ceramic materials are currently being developed. The technology is also notable for the large object sizes.

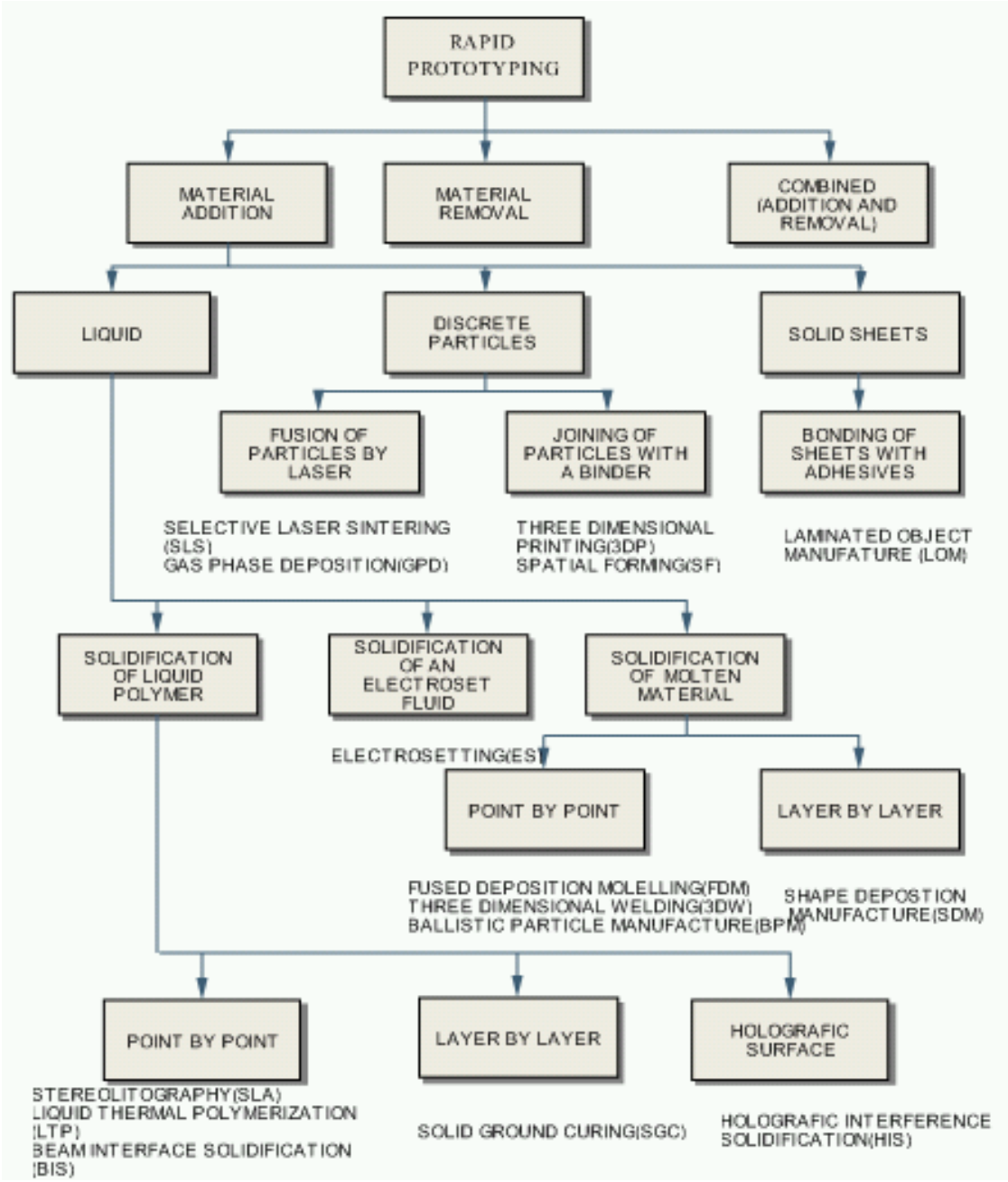


Figure A.1. Classification of RP (After Gebhardt, 2003)

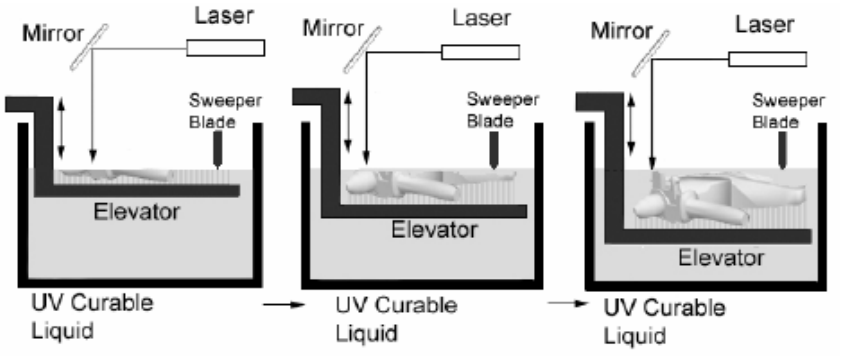


Figure A.2. The working principle of SLA (Lynn, 1998)

Table A.1. Main feature of SLA

Process	A low-power ultraviolet laser beam is moved at the surface of a vat of photocurable liquid polymer, producing a single layer of solidified resin; The initial layer is then lowered incrementally by the height of the next slice, whereupon the layer is recoated with resin and another is traced on top of it. This procedure is repeated until the entire part is fabricated.
Materials	Photopolymers based on acrylic- vinyl or epoxy resins
Accuracy	± 0.05 - 0.1 mm
Layer-thickness	0.1 - 0.5 mm
Max. dimension	600 mm x 600 mm x 400 mm
Advantages	High resolution; e.g. for integral parts with fine and complex structures with many different geometry elements, ribs, guiding, suspensions; Any geometrical shape can be made with virtually no limitation; Oldest commercial available process large selection of machines
Disadvantages	Labor requirements for post processing, especially cleaning; Supports for overhangs and cavities required; Accuracy not in the range of mechanical part manufacturing; Restricted areas of application due to given material properties; Risks of curl and warpage.
Applications	Master models for tools that can be used for pre series production tests; Medical models, form-fit functions for assembly tests.

SLA models are also sensitive to the environment and can distort although developments in SLA resins are helping to combat this. Another disadvantage of

SLA is the material selection which is limited to specifically processed photo sensitive resins. During model build, it is necessary to have supports for model as raw material is liquid. Also SLA models require a lot of post processing. On the negative side, working with liquid materials can be messy and parts often require a post-curing operation in a separate oven-like apparatus for complete cure and stability.

A.1.2. Selective Laser Sintering (SLS)

In the SLS process, a modulated CO_2 laser beam follows the shape of a slice of a CAD generated object; it traces the object across a vat filled with a powder, heating the particles so they fuse or sinter together. After the initial layer is formed, powder is reapplied and the laser processes the next layer as shown in figure A.3.

The basic material consists of powders with particle sizes in the order of magnitude of 50 μm. Successive powder layers are spread on top of each other. After deposition, a CO_2 laser beam selectively binds the powder particles of the corresponding cross section of the product together (Chen, 1996; Barlow et all., 1991).

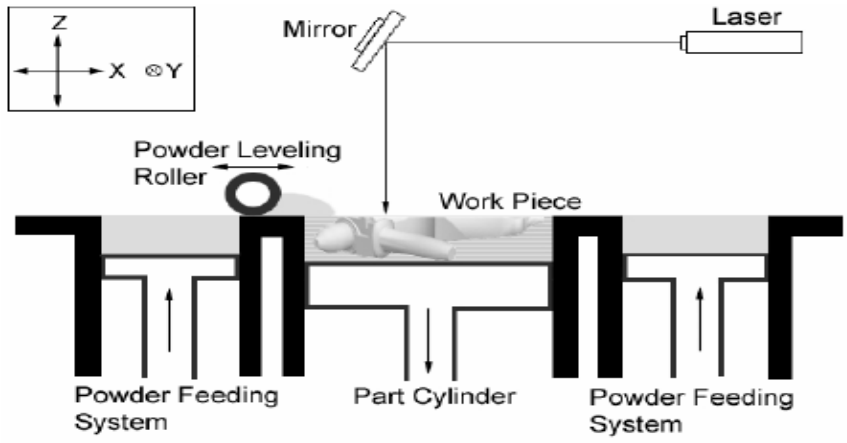


Figure A.3. The working principle of SLS (Kochan, 1993).

The use of thermoplastics, which means they can be melted out of the investment casting shells, be using a conventional autoclave. Among these, wax material is very similar to regular investment casting wax, making it very compatible with traditional investment casting techniques. Polycarbonate also can be melted out of casting shells by autoclaving. The SLS surface finish is rougher than many other LM processes. The surface finish of investment cast parts can be improved by coating the patterns with wax before making the casting shell. Even with the wax coating, the rough surface finish of the SLS part is usually transferred to the final metal part. Prototypes of steel are manufactured by sintering of steel powder coated with binder (Anderson et all., 2002). The binders are burned out in a subsequent oven process and the components infiltrated with copper or tin around to increase their density. This process can be used for rapid tooling. Processing of typical design materials, still usually with smaller density compared to parts from die-casting respective injection molding. Infiltration process can increase density SLS offers significant opportunities for production of metal-based components and tooling systems. A summary of these considerations is reported in table A.2.

Table A.2. Main feature of SLS

Process	Layer wise sintering of powder materials through a laser beam
Materials	Thermoplastics, modeling wax, metals, metal powders, sand, ceramics; plastic powders like polystyrene, polycarbonate, and polyamide polycarbonate, polyvinilchloride (PVC), nylon, croning sand for building, sand casting cores, metal and investment casting wax; virtually any materials
Accuracy	± 0.1 - 0.2 mm
Layer-thickness	0.1 - 0.2 mm
Max. dimension	350 x 350 x 600 mm³
Advantages	Parts do not require any post-curing except when ceramics are used; Production, from powder to part, is generally a same day process; There is no need to create a structure to support overhanging geometry.
Disadvantages	During solidification, it may happen that on the borderline additional powder is hardening. This results in a raw appearance of the part surface;

	Toxic gases emitted from the fusing process have to be handled carefully; The roughness of surface lead to lowered mechanical properties.
Applications	Visual representation and functional tough prototypes; Cast metal parts (by use of wax); Short run and soft tooling; For design, technical and functional studies; Patterns for vacuum, die, fine and sand casting.

A.1.3. Fused Deposition Modeling (FDM)

FDM process developed by Stratasys Inc. (De Jager, 2000) constructs parts based on deposition of extruded thermoplastic materials. In this process, a spool of thermoplastic filament feeds into a heated FDM extrusion head, consisting of a heater and a nozzle at the end. The movement of the FDM head is controlled by computer. Inside the flying extrusion head, the filament is melted into liquid (1^0 above the melting temperature) by a resistant heater. The head traces an exact outline of each cross-section layer of the part on a table (build platform) that moves in the z direction. As the head moves horizontally in the x and y axes over the table, the thermoplastic material is extruded out the nozzle by a precision pump. The material solidifies in 1/10 seconds as it is directed on to the workplace. After one layer is finished, the table moves down a programmed distance in the z direction for the building of the next layer. Each layer is bonded to the previous layer through thermal heating. The entire system is contained within a chamber which is held at a temperature just below the melting point of the plastic. Figure A.4. illustrates the working principle of FDM and main feature of FDM is shown in table A.3.

Table A.3. Main feature of FDM

Process	Melted plastic is built up layer wise by extrusion nozzle
Materials	Plastics like PA, PE, ABS, modeling wax, powders, Thermoplastics
Accuracy	± 0.127 mm
Layer-thickness	0.025 - 1.27 mm
Max. dimension	254 x 254 x 254 mm^3

Advantages	Quick and cheap generation of models; No toxic chemicals, or liquid polymer bath ; System does not waste material during or after producing the model; Does not require clean-up; Materials can be changed quickly; Low temperatures, between 70°C and 140°C depending on material; No sensitive laser applied ; Colour change options are available;
Disadvantages	Limited part complexity; Restricted accuracy due to the shape of the material used; Support structures needed; Post-processing for support removal; Mechanical strength is limited for mechanical testing;
Applications	Thin parts can be produced fast and quite good. Conceptual modeling, fit, form and functional models for further manufacturing procedures like: Investment casting, injection molding, vacuum casting, metal injection molding, and fine casting

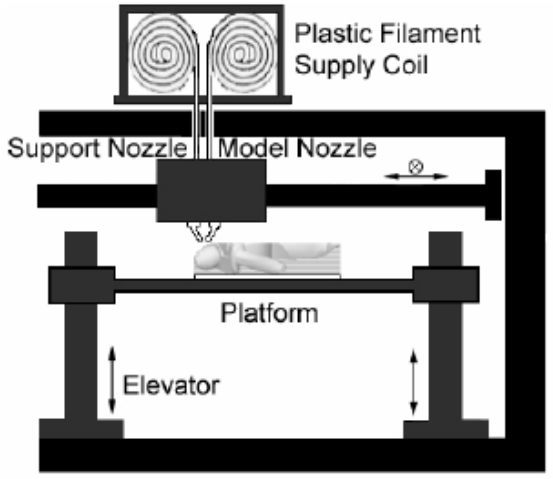


Figure A.4. The working principle of FDM (Burns, 1993)

A.1.4. Laminated Object Manufacturing (LOM)

The LOM process produce parts from bonded paper, plastic, metal and composite sheet stock (Feygin, 1988). LOM machines bond a layer of sheet material to a stack of previously formed laminations and then a laser beam follows the

contour of a part of a cross-section generated by CAD to cut it to the required shape. The layers can be glued or welded together. The excess material of every sheet is either removed by vacuum suction or remains as the next layer's support. Figure A.5. shows the working principle of LOM and the features of LOM are shown in table A.4.

Table A.4. Main feature of LOM

Process	A laser cut material foils in accordance with the model that are layer wise bonded on each other
Materials	Paper, plastic metal and composite sheet stock
Accuracy	± 0.1 mm
Layer-thickness	0.076 - 0.203 mm
Max. dimension	813 x 5590 x 508 mm^3
Advantages	Largest workspace for parts available on market; Low material costs; Much faster than competitive techniques; Produces virtually no internal stress and associated undesirable deformation; Complex parts with undercuts; Large variety of materials; Non-toxic materials; No need for supports during build;
Disadvantages	Stability of the objects is limited by the bonding strength of the glued layers; Not well suited for manufacturing parts with thin walls in the z-direction: Hollow parts must be fabricated as two parts in order to get an removable subtractive part of model Post processing for removal of subtractive part of model needed; Paper must be protected against moisture absorption; rough surface finish; Different properties of material in direction of laminate;
Applications	Conceptual design, used for large bulky models as patterns for sand casting, fine casting Models for silicon molds, injection molding fabricating of tools

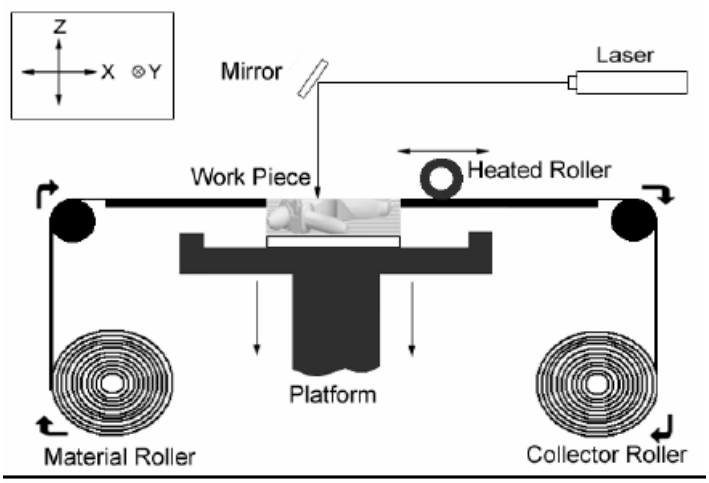


Figure A.5. The working principle of LOM (Feygin, 1998)

A.1.5. Three-Dimensional Printing (3DP)

Three dimensional printing was developed at MIT (MIT). It's often used as a direct manufacturing process as well as for rapid prototyping. The process starts by depositing a layer of powder object material at the top of a fabrication chamber. To accomplish this, a measured quantity of powder is first dispensed from a similar supply chamber by moving a piston upward incrementally. The roller then distributes and compresses the powder at the top of the fabrication chamber. The multi-channel jetting head subsequently deposits a liquid adhesive in a two dimensional pattern onto the layer of the powder which becomes bonded in the areas where the adhesive is deposited to form a layer of the object. Once a layer is completed, the fabrication piston moves down by the thickness of a layer and the process is repeated until the entire object is formed within the powder bed. After completion, the object is elevated and the extra powder brushed away leaving a "green" object. No external supports are required during fabrication since the powder bed supports overhangs.

Three dimensional printing offers the advantages of speedy fabrication and low materials cost. In fact, it's probably the fastest of all RP methods. Recently color output has also become available. However, there are limitations on resolution,

surface finish, part fragility and available materials. The closest competitor to this process is probably FDM. Figure A.6 shows the working process of 3DP.

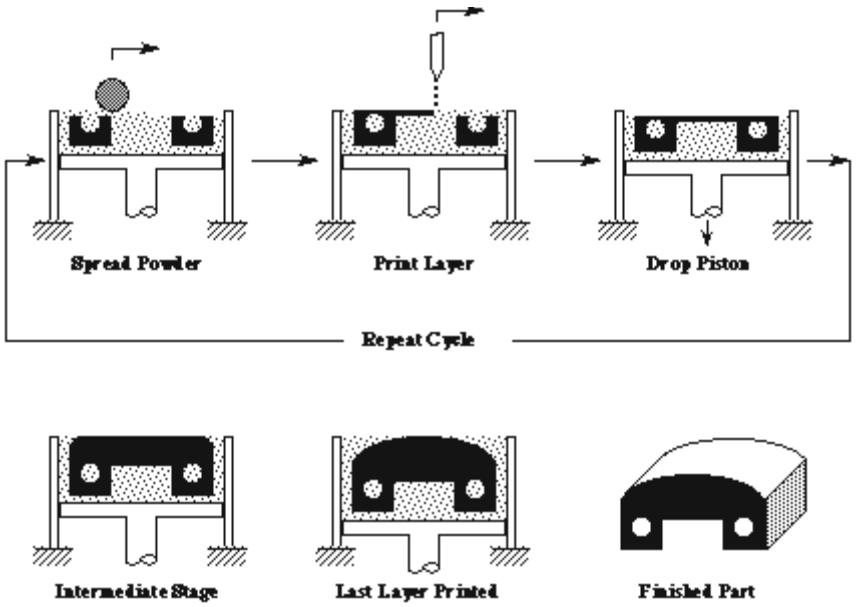


Figure A.6. The working principle of 3DP ((Dimitrov, 2006)

B.1. Applications of RP

B.1.1 Applications in Design

CAD Model Verification: This is the initial objective and strength of RP systems, in that designers often need the physical part to confirm the design that is created in the CAD system. This is especially important for parts or products designed to fulfill aesthetic functions or that are intricately designed to fulfill functional requirements.

Visualizing Objects: Designs created on CAD systems need to be communicated not only amongst designers within the same team, but also to other departments, like manufacturing and marketing. Thus, there is a need to create objects from the CAD designs for visualization so that all these people will be referring to the same object in any communications.

Proof of Concept: Proof of concept relates to the adaptation of specific details to an object environment or aesthetic aspects or of specific details of the design on the functional performance of a desired task or purpose.

Marketing and Commercial Applications: The marketing or commercial departments require a physical model for presentation and evaluation purposes, especially for assessment of the design as a whole. The mock-up or presentation model can even be used to produce promotional brochures and related materials for marketing and advertising even before the actual product becomes available.

B.1.2. Applications in Engineering, Analysis and Planning

Creating a physical model for visualization or proofing purposes, designers are interested in the engineering aspects of their designs. This invariably relates to the functions of the design. RP technologies become important as they are able to provide the information necessary to ensure sound engineering and function of the product. This makes it more attractive and also save development time and reduce costs (Chua et all., 2003).

Scaling: RP technology allows easy scaling down or up of the size of a model by scaling the original CAD model. In a case of designing bottles for perfumes with different holding capacities, the designer can simply scale the CAD model appropriately for the desired capacities and view the renderings on the CAD software. With the selected or preferred capacities determined, the CAD data can be changed accordingly to create the corresponding RP model for visualization and verification purposes.

Form and Fit: Other than dealing with sizes, volumes and forms have to be considered from the aesthetics and functional standpoint as well. How a part fits into a design and its environment are important aspects, which have to be addressed. The model will be used to evaluate how it satisfies both aesthetic and functional requirements. Form and fit models are commonly used in the automotive industries. They can also be used for industries involved in aerospace, consumer electronic products and appliances.

Flow Analysis: Designs of components that affect or are affected by air or fluid flow cannot be easily modified if produced by the traditional manufacturing methods. However, if the original 3D design data can be stored in a computer model, then any change of object data based on some specific tests can be realized with computer support. The flow dynamics of these products can be computer simulated with software. Experiments with 3D physical models are frequently required to study product performance in air and liquid flow. Such models can be easily built using RP technology. Modifications in design can be done on computer and rebuilt for re-testing very much faster than using traditional prototyping methods. Flow analyses are also useful for studying the inner sections of inlet manifolds, exhaust pipes, replacement heart valves or similar products that have complex internal geometries. Typically, flow analyses are necessary for products manufactured in the aerospace, automotive, and biomedical industries (Wang et all., 2000).

Stress Analysis: In stress analysis using mechanical, photo-optical methods or physical replicas of the part being analyzed are necessary. If the material properties or features of the RP technologies generated objects are

similar to those of the actual functional parts, they can be used in these analytical methods to determine the stress distribution of the product.

Mock-Up Parts: Mock-up parts are used for final testing of different aspects of the parts. Generally, mock-up parts are assembled into the complete product and functionally tested at pre-determined conditions, e.g., for fatigue. Some RP techniques are able to generate mock-ups very quickly to fulfill these functional tests before the design is finalized.

Pre-Production Parts: In cases where mass-production will be introduced once the prototype design has been tested and confirmed, pilot-production runs of ten or more parts are usual. The pilot-production parts are used to confirm tooling design and specifications. The necessary accessory equipment, such as fixtures, chucks, special tools and measurement devices required for the mass-production process are prepared and checked. Many of the RP methods are able to quickly produce pilot-production parts, thus helping to shorten the process development time, thereby accelerating the overall time-to-market process.

Diagnostic and Surgical Operation Planning: In combining engineering prototyping methodologies with surgical procedures, RP models can complement various imaging systems, such as Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) scanning, to produce anatomical models for diagnostic purposes. These RP models can also be used for surgical and reconstruction operation planning. This is especially useful in surgical procedures that have to be carried out by different teams of medical specialists and where interdepartmental communication is of essence (Swaelans, 1993; Adachi et all., 1998; Stoker et all., 1992).

Design and Fabrication of Custom Prosthesis and Implant: RP can be applied to the design and fabrication of customized prostheses and implants. A prosthesis or implant can be made from anatomical data inputs from imaging systems, e.g., laser scanning and computed tomography. In cases, such as having to produce ear prostheses, a scan profile can be taken of the good ear to create a computer-mirrored exact replica replacement using RP technology (Koyayashi et all., 1992). These models can be further refined and processed to create the actual

prostheses or implants to be used directly on a patient. The ability to efficiently customize and produce such prostheses and implants is important as standard sizes are not always an ideal fit for the patient. Also, a less than ideal fit especially for artificial joints and weight bearing implants can often result in accumulative problems and damage to the surrounding tissue structures.

B.1.3. Applications in Manufacturing and Tooling

Rapid tooling is the ability to produce multiple copies of a prototype with functional material properties in short lead-times. Apart from mechanical properties, the material can also include functionalities such as color dyes, transparency, flexibility and the like.

Rapid tooling can be classified into soft or hard and direct or indirect tooling (Kulkarni et all, 2000). Soft tooling, typically made of silicon rubber, epoxy resins, low melting point alloys and foundry sands, generally allows for only single casts or for small batch production runs. Hard tooling, on the other hand, usually made from tool steels, generally allows for longer production runs.

Direct tooling is referred to when the tool or die is created directly by the RP process. As an example in the case of injection molding, the main cavity and cores, runner, gating and ejection systems can be produced directly using the RP process. In indirect tooling, on the other hand, only the master pattern is created using the RP process. A mold, made of silicon rubber, epoxy resin, low melting point metal, or ceramic, is then created from the master pattern.

Direct Soft Tooling: This is where the molding tool is produced directly by the RP systems. Such tooling can be used for liquid metal sand casting in which the mold is destroyed after a single cast. These are generally used in the injection molding of plastic components and can withstand up to between 100 to 1000 shots (Wilkening, 1996; Tsang, 1996). As these molding tools can typically only support a single cast or small batch production run before breaking down, they are classified as soft tooling.

Indirect Soft Tooling: In this rapid tooling method, a master pattern is first produced using RP. From the master pattern, a mold tooling can be built out of an array of materials such as silicon rubber, epoxy resin, low melting point metals and ceramics.

Direct Hard Tooling: The advantages of hard tooling produced by RP methods are fast turnaround times to create highly complex-shaped mold tooling for high volume production. The fast response to modifications in generic designs can be almost immediate (Chua et all., 1999; Schaer, 1995; Male et all., 1996; Bettay, 1995).

Indirect Hard Tooling: In general, indirect methods for producing hard tools for plastic injection molding generally make use of casting of liquid metals or steel powders in a binder system (Wenus et all., 1996; Soar et all., 1996). For the latter, debinding, sintering and infiltration with a secondary material are usually carried out as post-processes.

Die Casting: Die casting is a manufacturing process for producing accurately dimensioned, sharply defined, smooth or textured surface metal parts. It is accomplished by forcing molten metal under high pressure into reusable metal dies.

LM technologies can be combined with traditional casting processes to produce metal/alloy prototypes of the die-cast part or even cast metal tooling for producing prototypes. Metal/alloy prototypes are usually made using sand or plaster molds, although investment casting can also be used. Patterns for sand or plaster molds are usually made from epoxy, polyurethane plastic or rubber, from parted LM models to enable a better surface finish in the cast prototype (Chalasani, 2000; 2001). LM is also used to create scaled patterns of the part to be produced. That pattern is in turn used to create plaster molds which are then used to cast prototypes in zinc, aluminum and magnesium. The advantages of this prototyping are that prototypes can be manufactured for a low cost (2-5% of the cost of the die), fast speed (3-4 weeks) and are a good simulation of the production die cast part.

Other die casting industry applications of LM are focused on foundry pattern fabrication for the gravity casting process, commonly referred to as rapid prototype simulated die casting. RP simulated die castings provide a suitable substitute of the

part for the early design stage, but compromise mechanical properties such as yield strength and ultimate tensile strength.

Investment Casting: Many LM processes (FDM, SLS, etc.) can manufacture parts in investment casting wax. These parts are being used as patterns in the investment casting of complex metal shapes. For a long time, the majority of dies used for investment casting operations needed to be machined from blocks of metal, yielding cavities to produce the wax pattern. Instead of doing that, now the CAD geometry of the part can be reversed to form the design for the injection tool. This injection tool can be made on an LM machine to act as a die to produce usable wax patterns (Chua et all., 1999a; 1999b).

By using the alumina and silica ceramic SLA systems, shells and cores for investment casting can be directly fabricated. Also, functional prototypes can be produced directly in alumina or silica.

C.1. Sections of an IGES ASCII file

IGES data can be represented in either ASCII or binary format. Fixed format beginning with its first character, the file consists of 80-column lines. Lines are grouped into sections. Each line contains section-specific data fields in columns 1-72, an identifying letter code in column 73, and an ascending sequence number in columns 74-80. Within each section, the sequence number begins at 1 and is incremented by 1 for each line. Sequence numbers are right-justified in their field with leading space or leading zero fill as shown in figure C.1.

Flag section: This section of the file is used to indicate whether the file is in the Binary format or in the Compressed ASCII format. This section is optional.

Start Section: This section of the file is designed to provide a human-readable prologue to the file. There must be at least one start record. All records in this section have the letter S in column 73 and sequence number in column 74 through 80. Columns 1-73 need not be formatted in any special way except that the ASCII character set must be used.

Global Section: This section contains information describing the pre-processor and information needed by the post-processor to handle the file. All records in this section have a G in column 73. The parameters in the global section contain information that describes the parameter delimiter and record delimiter characters, file name, system ID, units, date and time of the file generation, file version number, etc.

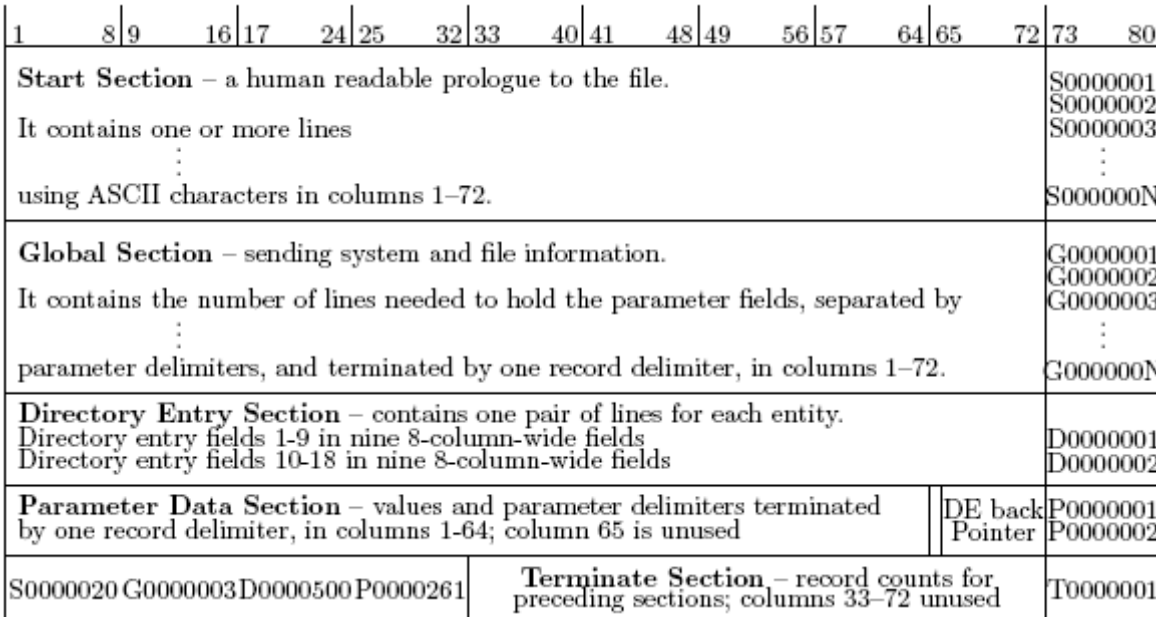


Figure C.1. General file structure of the fixed format

Directory Entry Section (DE): The Directory Entry Section has one directory entry for each entry in the file. The directory entry for each entity is fixed in size and contains twenty fields of eight characters each, spread over two consecutive eighty character lines. The data in each section is right justified and consists of either pointer constants or integer constants as shown in figure C.2. The purpose of this section is to provide an index for the file and to contain general attribute information for each entity. Each entity has an identification number which describes the type of the entity and hence how the corresponding data is represented in the parameter data section. The 1st and 11th fields contain the identifying number. The second field contains a pointer to the first line of the parameter data record for the entity. Other fields contains information line style, color, level of drawing on which the drawing resides, view data, entity label, etc. Column 73 contains the letter D for this section and columns 74-80 contain the sequence number within the section.

1 8	9 16	17 24	25 32	33 40	41 48	49 56	57 64	65 72	73 80
(1) Entity Type Number #	(2) Parameter Data ⇒	(3) Structure #,⇒	(4) Line Font Pattern #,⇒	(5) Level #,⇒	(6) View 0,⇒	(7) Transformation Matrix 0,⇒	(8) Label Display Assoc. 0,⇒	(9) Status Number #	(10) Sequence Number D #
(11) Entity Type Number #	(12) Line Weight Number #	(13) Color Number #,⇒	(14) Parameter Line Count #	(15) Form Number #	(16) Reserved	(17) Reserved	(18) Entity Label	(19) Entity Subscript Number #	(20) Sequence Number D # + 1

Nomenclature:

(n) - Field number n
\# - Integer
⇒ - Pointer
#,⇒ - Integer or pointer (pointer is negated)
0,⇒ - Zero or pointer

Figure C.2. Format of the Directory Entry (DE) Section

Parameter Data Section (PD): The first field always contains the entity type number. The remainder of the record contains data to define the particular entity. Column 73 contains the code letter P for this section, and columns 74-80 contain the sequence number. Figure C.3. shows the line and circle entities in the PD section.

Field	1	2	3	4	5	6	7	8	…	73-80
Circle	100	X Y Z (Center of circle)			X_1 Y_1 (Start Point)		X_2 Y_2 (End Point)			Sequence Number
Line	100	X_1 Y_1 Z_1 (Start Point)			X_2 Y_2 Z_2 (End Point)					Sequence Number

Figure C.3. Format of the Parameter Data (PD) Section

Terminate Section: This section consists of only one line which terminates the file. The terminate section provides summary information about the number of lines used in each section of the whole file. Each field in the Terminate record contains a section identifier which is left-justified in the field and the last sequence number used in that section.

C.1.1. Representation of IGES Entities

As mentioned earlier, IGES is a standard file format for data defining the object drawing in 3D CAD systems in B-rep structure. The entry fields in IGES format consist of an object's geometric and topological information. The geometric information includes the definition of lines, planes, circles and other geometric entities for a given object and the topological information defining the relationships between the object's geometric components. The fundamental IGES entities, which are related to representing a part in B-rep structure are discussed in the following section to understand how these entities are defined.

C.1.1.1. Circular Arc (100)

A circular arc is a connected portion of circles which has distinct start and terminates points. The circular arc lies in a plane either coincident with or parallel to the X_T , Y_T plane.

A circular arc determines unique arc end points and an arc center point. By considering the arc end points to be enumerated and listed in an ordered manner, start point first, followed by terminate point, a direction with respect to definition space can be associated with the arc.

C.1.1.2. Composite Curve (102)

A composite curve is a continuous curve that results from the grouping of certain individual constituent entities into a logical unit. Composite curves is defined as an ordered list of entities consisting of point, connect point and parameterized curve as shown in figure C.4. The list of entities appears in the parameter data entry.

A composite curve is a directed curve, having a start point and a terminate point. The direction of the composite curve is determined by the direction of the constituent curve entities in the following way: The start point for the composite curve is the start point of the first curve appearing in the defining list. The terminate

point for the composite curve is the terminate point of the last curve entity appearing in the defining list. Within the defining list itself, the terminate point of each constituent curve entity has the same coordinates as the start point of the succeeding curve entity.

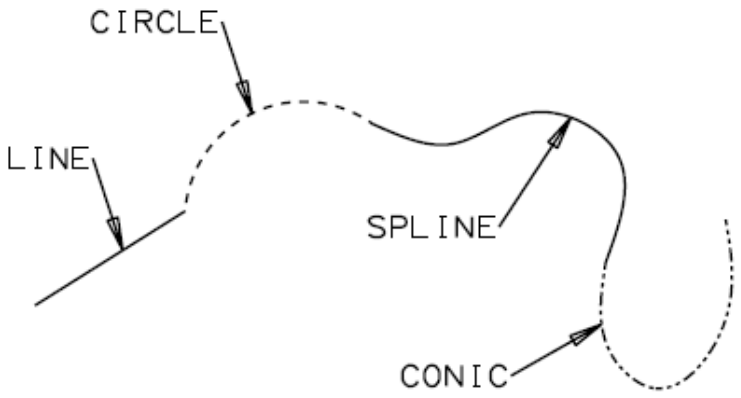


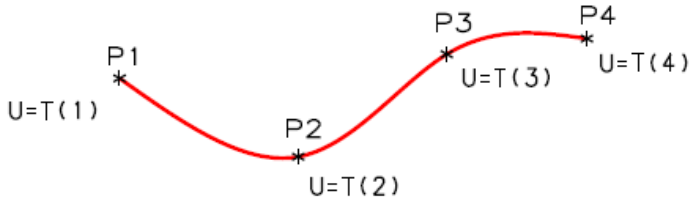
Figure C.4. Composite curve

C.1.1.3. Line Entity (110)

A line is a bounded, connected portion of a straight line which has distinct start and terminates points. A line is defined by its end points. Each end point is specified relative to definition space by triple coordinates. With respect to definition space, a direction is associated with the line by considering the start point to be listed first and the terminate point second.

C.1.1.4. Parametric Spline Curve Entity (112)

The parametric spline curve is a sequence of parametric polynomial segments. The CTYPE value in Parameter 1 indicates the type of curve as it was represented in the preprocessing system before conversion to this entity as shown in figure C.5.



Curve=(X(u), Y(u), Z(u)), For $T(1) \leq u \leq T(N+1)$

N=3 segment

$P_1=(A_x(1), A_y(1), A_z(1))$

$P_2=(A_x(2), A_y(2), A_z(2))$

$P_3=(A_x(3), A_y(3), A_z(3))$

Figure C.5. Parametric spline curve

The N polynomial segments are delimited by the breakpoints T(1), T(2), ..., T(N + 1). To enable determination of the terminate point and derivatives without computing the polynomials, the N-th polynomials and their derivatives are evaluated at u = T(N+1). These data are divided by appropriate factorials and stored the polynomial coefficients. For example, the Parameter Data name TPY3 is used to designate 1/3! times the third derivative of the Y polynomial for the Nth segment evaluated at u = T(N +1) , the parameter value corresponding to the terminate point. Table C.1. shows parametric spline curve database information

Table C.1. Parametric spline curve (112) information

Name	**Description**
CTYPE	Spline Type: 1=Linear 2=Quadratic 3=Cubic 4=Wilson-Fowler 5=Modified Wilson-Fowler 6=B-spline
H	Degree of continuity with respect to arc length
NDIM	Number of dimensions: 2=planar 3=nonplanar
N	Number of segments

T(1)	First break point of piecewise polynomial
… …	
T(N+1)	Last break point of piecewise polynomial
$A_X(1)$	X coordinate polynomial
$B_X(1)$	
$C_X(1)$	
$A_Y(1)$	Y coordinate polynomial
$B_Y(1)$	
$C_Y(1)$	
$A_Z(1)$	Z coordinate polynomial
$B_Z(1)$	
$C_Z(1)$	
	Subsequent X, Y, Z polynomials concluding with the twelve coefficients of the N_{th} polynomial segment.

C.1.1.5. Rational B-Spline Curve Entity (126)

The rational B-spline curve may represent analytic curves. If the rational B-spline curve represents a preferred curve type, the form number corresponds to the preferred type. The preference order is from 1 through 5, followed by 0. For example, if the curve is a circle or circular arc, the form number will be set to 2 as shown in figure C.6.

If the curve lies entirely within a unique plane, the planar flag (PROP1) will be set to 1; otherwise it will be set to 0. If it is set to 1, the plane normal will contain a unit vector normal to the plane containing the curve. These fields will exist but are ignored if the curve is non-planar.

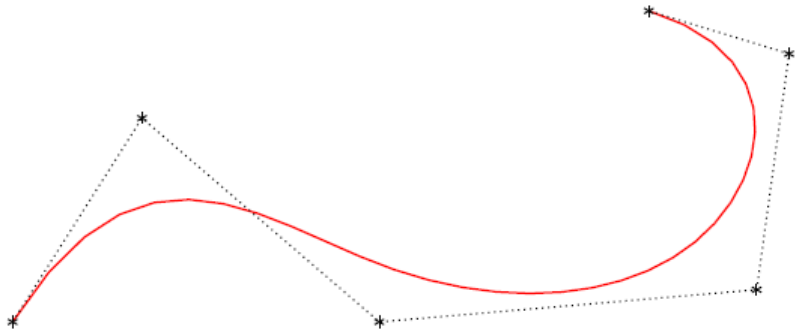


Figure C.6. Rational B-Spline Curve (Type 126)

If the beginning and ending points on the curve, as defined by evaluating the curve at the starting and ending parameter values (i.e., V(0) and V(1)), are coincident, the curve is closed and PROP2 will be set to 1. If they are not coincident, PROP2 will be set to 0.

If the curve is rational (does not have all weights equal), PROP3 will be set to 0. If all weights are equal to each other, the curve is polynomial and PROP3 will be set to 1. The curve is polynomial since in this case all weights cancel and the denominator reduces to one.

If the curve is periodic with respect to its parametric variable, PROP4 will be set to 1; otherwise, PROP4 will be set to 0. The periodic flag is to be interpreted as purely informational; the curves which are flagged to be periodic are to be evaluated exactly the same as in the non-periodic case. Table C.2. shows rational B-spline curve (126) information.

Table C.2. Rational B-spline curve (126) information

Name	**Description**
K	Upper index of sum
M	Degree of basis functions
PROP1	0 = nonplanar, 1 = planar
PROP2	0 = open curve, 1 = closed curve
PROP3	0 = rational, 1 = polynomial
PROP4	0 = nonperiodic, 1 = periodic
u_o	First value of knot sequence
… …	
U_{n+p+1}	Last value of knot sequence
w_o	First weight
… …	
w_N	Last weight
P_0x	First control point (x component)
P_0y	First control point (y component)
P_0z	First control point (z component)
… …	
P_Nx	Last control point (x component)
P_Ny	Last control point (y component)
P_Nz	Last control point (z component)
u_{start}	Starting parameter value
u_{end}	Ending parameter value

	Unit normal
n^x	Unit normal (if curve is planar)
n^y	Unit normal
n^z	Unit normal

C.1.1.6. Rational B-Spline Surface Entity (128)

If the rational B-spline surface represents a preferred surface type, the form number corresponds to the most preferred type. The preference order is from 1 through 9 followed by 0. For example, if the surface is a right circular cylinder, the form number will be set to 2. If the surface is not one of the preferred types, the form number will be set to 0. If the surface is rational (does not have all weights equal), PROP3 will be set to 0. If all weights are equal to each other, the surface is polynomial and PROP3 will be set to 1. The surface is polynomial since in this case all weights cancel and the denominator reduces to one.

If the surface is periodic with respect to the first parametric variable, PROP4 will be set to 1; otherwise, PROP4 will be set to 0. If the surface is periodic with respect to the second parametric variable, PROP5 will be set to 1; otherwise, PROP5 will be set to 0. Table C.3. shows rational B-Spline surface information

Table C.3. Rational B-Spline surface information

Name	**Description**
M	Number of control points in the u direction
N	Number of control points in the v direction
m	Degree in the u direction
n	Degree in the v direction
PROP1	1 = Closed in first parametric variable direction 0 = Not closed
PROP2	1 = Closed in second parametric variable direction 0 = Not closed
PROP3	0 = Rational 1 = Polynomial
PROP4	0 = Non-periodic in first parametric variable direction 1 = Periodic in first parametric variable direction
PROP5	0 = Non-periodic in second parametric variable direction 1 = Periodic in second parametric variable

	direction
u_o	First value of knot in u
… …	
u_m	Last value of knot in u
v_o	First value of knot in u
… …	
v_n	Last value of knot in u
$w_{0.0}$	First weight
$w_{1.0}$	second weight
… …	
$w_{m,N}$	Last weight
$P_{0,0}x$	First control point (x)
$P_{0,0}y$	First control point (y)
$P_{0,0}z$	First control point (z)
$P_{1,0}x$	second control point (x)
$P_{1,0}y$	second control point (y)
$P_{1,0}z$	second control point (z)
… …	
$P_{M,N}x$	Last control point (x)
$P_{M,N}y$	Last control point (y)
$P_{M,N}z$	Last control point (z)
u_{start}	Starting parameter value in u
u_{end}	Ending parameter value in u
v_{start}	Starting parameter value in v
v_{end}	Ending parameter value in u

C.1.1.7 Transformation Matrix (124)

This entity can give the relative location information between two coordinate systems, X_0, Y_0, Z_0 coordinate system and X_T, Y_T, Z_T coordinate system.

$$\begin{pmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{pmatrix} X \begin{pmatrix} X_0 \\ Y_0 \\ X_0 \end{pmatrix} + \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} = \begin{pmatrix} X_T \\ Y_T \\ X_T \end{pmatrix} \tag{C.1}$$

where $\begin{vmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{vmatrix} = 1$

C.1.1.8. Surface of Revolution (120)

A surface is created by rotating the generatrix about the axis of rotation from the start position to the terminal position. The axis of rotation is a line entity. The generatrix may be a conic arc, line, circular arc or composite curve. The angles of rotation are counterclockwise about the positive direction of rotation axis.