Integration of Rapid Prototyping Technology with CAD/CAM

By

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This thesis is submitted as fulfilment of the

requirement for the award of degree of

Master Of Engineering (M. Eng) by research

to

Dublin City University

August 2004

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School of Mechanical & Manufacturing Engineering

Declaration

I hereby certify that this material, which I now submit for assessment on the programme of study leading to the award of Master of Engineering is entirely my own work and has not been taken from the work of others save to the extent that such work has been cited and acknowledged within the text of my work

Signed: ______ (Candidate)

ID No.:99145936

Date: August 2004

Acknowledgements

I would like to express my sincere thanks and gratitude to Dr Paul Young for his excellent supervision, helpful advice and constant encouragement and guidance. Without his support and continuous advice throughout this research it would not have been possible to finish this thesis. I am honoured to have him as my supervisor for this research.

Many thanks to professor M.S.J Hashmi for his guidance and helpful advice.

Thanks to Keith Hickey, school IT system administrator, for offering his time and expertise when required.

Thanks to my fellow graduate students for their spontaneous support and comments.

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Abstract

Rapid prototyping(RP) is a relatively new technology, which still faces challenges and a lot of problems in different stages of the process; this makes RP technology available only using very specialised equipment and very sophisticated software. This project is a step towards expanding the use of this technology, easing some of the difficulties and knowledge required to use RP systems.

Using existing CAD/CAM software, which is well understood and normally used in machining operations the software developed manipulates the machining code from the AlphaCAM package and generates code and instructions suitable for RP technology.

Two user-friendly programs were developed using Visual Basic to generate control code for a wax droplet RP system previously developed. CAD/RP follows the traditional method in RP and generates control instructions for the system from a STL file. The CNC/RP software is designed to generate control instructions for the system to build a prototype from CNC code, generated using AlphaCAM. This work, undertaken by the author, broadens the application of layer manufacturing where functional prototype parts are produced.

TABLE OF CONTENTS

LIST OF FIGURES

Title | Page

Chapter 1 Introduction

Until recently, prototypes were still constructed by skilled craftsmen from 2D drawings, adding weeks or months to the product development time. Currently product design is becoming more complex, while the need for reducing the time to market has increased.

CAD/CAM technology has provided a new way to produce accurate parts directly from CAD models in a few hours for a fraction of manufacturing cost, with little need for human intervention.

While there are a number of vendors using different technologies in their particular equipment, most of the additional RP systems work under the same fundamental principals. This consists of 3D CAD data, in a specific file format usually (STL), oriented in an optimal build position and direction, the file is then sliced numerically into layers representing horizontal cross-sections of the part. The RP machine then fabricates each layer and bonds it to the previous layer, starting from the bottom section and working up to the top until the part is complete [1,2].

This technology allows companies to produce physical models of their designs more often, allowing them to check the assembly and function of a design while spending less time and money. It has been claimed that RP can cut the cost of developing new products by up to 70%, and the time to market by 90% [3, 4].

Rapid prototyping is a relatively new technology, which is still facing a lot of problems in different stages of the process; this makes RP technology available only using specialised equipment and specialist trained staff. This project is a step towards spreading this technology and to ease some of the difficulties by using existing CAD/CAM software, which is commonly used in machining operations, through the introduction of a software package, to manipulate the CNC code and generate instructions suitable for RP.

The developed software scans the CNC code, which is generated using AlphaCAM, manipulates the tool path, simulates the deposition of wax, filtering deposition of excess material in some areas, and then translates the CNC code to X-language codes, which are the PC23 indexer instructions to drive the motors. To prove the effectiveness of the solution some examples were built using this strategy and a wax droplet RP system previously developed in DCU.

The wax droplet RP system consists of a heated cylinder containing the wax and a plunger head fitted in the cylinder to increase the pressure inside the cylinder. Then this deposits one drop then retracts to hold the wax inside the cylinder. An indexer is used to drive the three motors, two motors to provide the X-Y movement while a third is to deposit the wax. The indexer receives the instructions from a personal computer in a special instruction set called X-language.

This approach can solve many problems at different stages of the rapid prototyping process, such as data transfer, slicing the geometry, tool path generation, building the support structure and fabricating multiple materials. The work undertaken by the author contributes specially to layer manufacturing where functional parts are produced and more control over the building operation is needed. As in the material removal technologies, where engineers control the machining operation and generate the CNC code to create different features on the part using a range of tools that are available for machining operations, addition technologies are now more controllable by varying the operation parameters. These parameters include as the layer thickness, the deposition diameter in some technologies or the laser beam within other technologies, the travel speed and touch angle. This is not only for the whole operation, but it could be varied for each feature to achieve the required property, especially when a large number of the product is needed.

Chapter 2 Overview Of Rapid Prototyping

Rapid Prototyping (RP) refers to fabrication of parts layer-by-layer. It involves adding raw material successively, in layers, to create a solid of a predefined shape. The process is fully automatic and it offers many advantages over traditional manufacturing processes.

There is a very big range of rapid prototyping technologies, but the basic technique for all of these RP methods follows the same five steps see Figure 1:

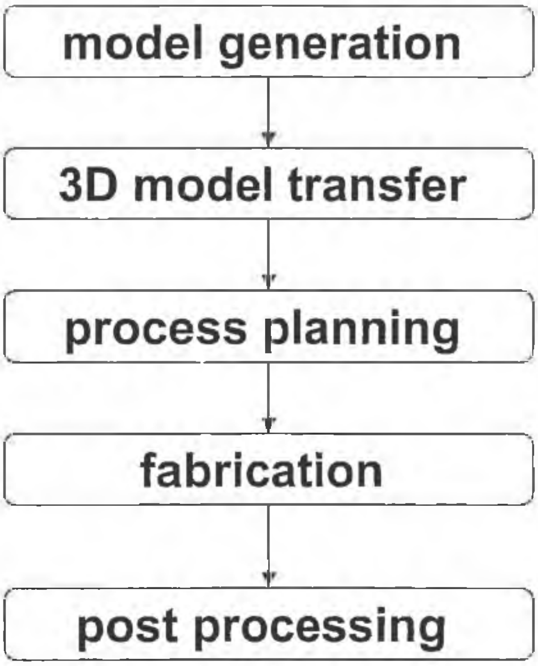


Figure 1 The Basic Technique of Rapid Prototyping

2.1 Model Generation

The first step to produce the part using RP technology is to put the design of the required part in a numerical data. There is a wide range of sources for 3-D model data input for RP process.

2.1.1 CAD Mode

Most of RP systems use a CAD model as the main source for the data input. The CAD model can be a solid model or a surface model [5].

A solid model is a complete mathematical representation of the shape of a physical object, it contains two types of data to describe the part, geometric data and topological data. Geometric data defines the basic shape, lines, curves, and surfaces. The topological data contains the connectivity relationship among the geometric components and allows the computer to determine the volume that is enclosed by the object's surfaces. There are many types of solid modellers in use, the most commonly used are: Constructive solid geometry, Boundary representation (B-rep), and Polyhedral modelling [2, 6].

A surface model defined by a number of surfaces with zero thickness is joined together to form the part. Since there is no topological data to define association between these surfaces, it is possible to have gaps or even missing surfaces. The surface model has to have a closed surface for use in rapid prototyping [6, 7].

2.1.2 Reverse engineering data

Reverse Engineering is the process of recreating an engineering design data from existing parts by acquiring the surface data using a laser scanning system, contact probe, digitisers, or computer vision. This technique is very useful when the engineering design is lost or when the physical model has gone through many design changes [8, 9, 10, 11].

2.2 3D Model Transfer

To fabricate any design in current rapid prototyping systems the 3-D model (surface or solid) has to be transferred to STL (standard transform language)[12] format, which is the most common standard interface between CAD and RP systems [1].

STL format was developed and published in 1987 by 3D systems for converting 3D CAD models for use in stereolithography and has become the de-facto standard for the data input for all types of RP systems [1, 2].

The STL file format is generated using a tessellation process, which generates triangles to represent the CAD model, these triangles are described by a set of X, Y and Z coordinates for each of three vertices, and a unit normal vector to indicate which side of the triangle contains the mass. STL file can be in ASCII or in binary format, the ASCII STL format file is larger but legible see Figure 2 [1, 6, 9].

```
solid  BOX              -----------------------------------------------------------------(1)
 facet normal -1.00000000E+000  0.00000000E+000  0.00000000E+000  ---(2)
  outer loop            -----------------------------------------------------------------(3)
   vertex -3.90508985E+001  4.27599077E+001  2.27695819E+001
   vertex -3.90508985E+001  4.27599077E+001 -2.23041810E+000      ---(4)
   vertex -3.90508985E+001  6.16805593E+000 -2.23041810E+000
  endloop               -----------------------------------------------------------------(5)
 endfacet               -----------------------------------------------------------------(6)
 facet normal -1.00000000E+000  0.00000000E+000  0.00000000E+000
  outer loop
   vertex -3.90508985E+001  6.16805593E+000 -2.23041810E+000
   vertex -3.90508985E+001  6.16805593E+000  2.27695819E+001
   vertex -3.90508985E+001  4.27599077E+001  2.27695819E+001
  endloop
 endfacet
.
.
.
endsolid  BOX           -----------------------------------------------------------------(7)
```

(1) The start of solid
(2) Identifies the material side
(3) The start of the triangle vertex
(4) x, y, z for each vertex
(5) End of the triangle vertex
(6) End of the triangle information
(7) End of the solid information

Figure 2 Example of STL file and description format ASCII representation

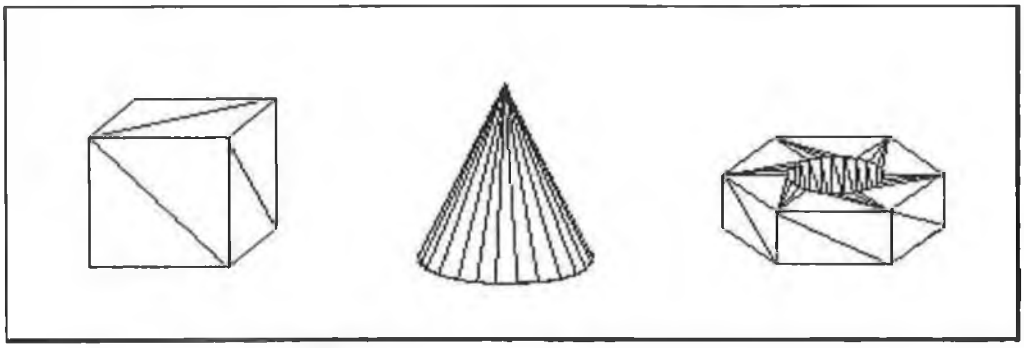


Figure 3 Example of many objects in STL format [13]

STL is a very simple format, yet contains the potential for defining any shape with any number of edges see Figure 3.

2.3 Process Planning

Process planning is a stage where the control instructions are generated and the process parameters are selected, at this stage the system and the operator carry out the following steps.

2.3.1 Select an orientation

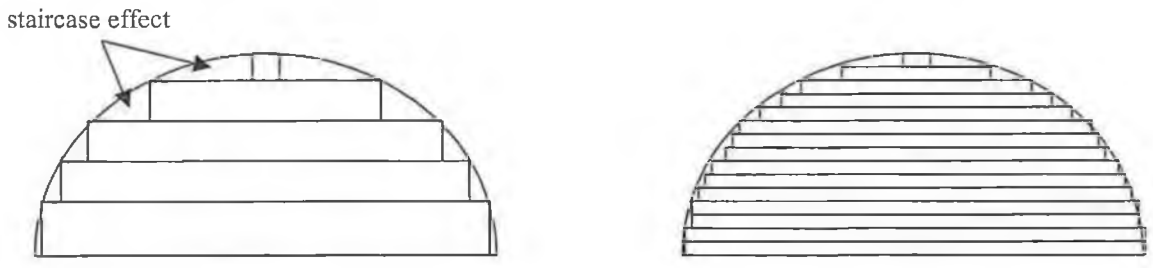
An optimal build direction has to be determined to improve part accuracy, the surface finish, assessing the need for support structures and to reduce the production time, which leads to minimizing the cost of producing the prototype [14, 15, 16].

2.3.2 Create supports

Some models have overhanging portions, which need support structures to build it. Some RP systems do not need to build support structures, where uncured material works as a support structure [5].

2.3.3 Slice the geometry

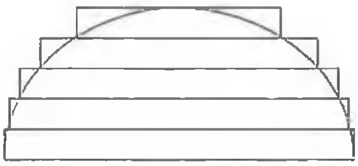
The STL model is mathematically sliced by intersecting it with horizontal planes. Each slice represents a cross-section data for the part. The layer thickness is the distance between these planes; if the layer thickness is small this results in a smooth part but increases the building time. If the layer thickness is large, the build time will be shorter while increasing the staircase effect [9, 17].



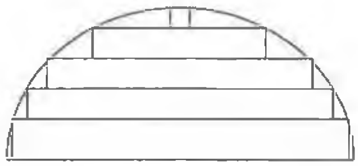
(a) Slicing with a large layer thickness (b) Slicing with smaller layer thickness

Figure 4 The effect of slicing with different layer thickness on the produced part accuracy

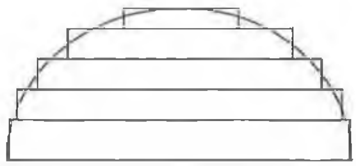
There are three types of slicing processes based on the way the allowances are distributed. The union of all the layers contains the required 3D object as shown in the first type of slicing in Figure 5a. This type of slicing is desirable where some allowance is required to finish the prototype. All the layers are contained inside the 3D object in the slicing method shown in the Figure 5b. This method is used where adding material to fill the cavities finishes the prototype. In the third method, the layers are distributed on both sides of the profile. This method gives the most accurate prototype [18].



(a) Slicing method in which the scallops enclose the desired profile



(b) Slicing method in which the desired profile encloses the scallops



(c) Slicing method in which the scallops are distributed on both sides of the desired profile

Figure 5 Three type of tolerance distribution while slicing

2.3.4 Contour filling and Build styles

After defining the cross-section of the slices, the interior of the slice has to be filled with the material in FDM or solidified with laser in some technology. There are many patterns used to fill the cross-section, for example using zigzag, cross-hatch raster or offset contour [5, 19]. Different deposition strategies affect the building time and the stiffness of the part in some systems [20].

2.3.5 Solid build styles

Below are some types used in Stereolithography.

a. **Accurate Clear Epoxy Solid (ACES)** This method is the most accurate build style, the interior of the part is almost wholly cured, it uses a hatch-spacing equivalent to half line width, see Figure 6, so all the solidified resin receives the same cumulative UV exposure and uses a layer border to define the part boundaries. The drawing time in this type is the longest compared to the other styles because most of the layer receives a double processing[20].

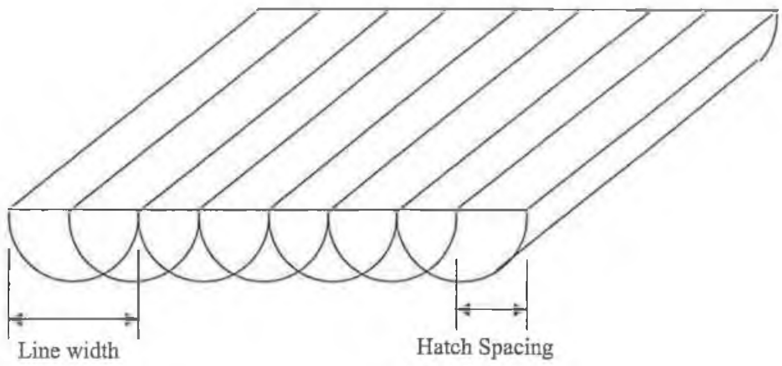


Figure 6 ACES build style

b. **Star Weave** The interior of the part is hatched with a series of grids. These grids are offset by half a hatching spacing see Figure 7. Every other layer and layer border creates the part boundaries. The grid lines do not touch one another and they are not attached to the part border to reduce the overall distortion. The draw time in this method is lower [20,21].

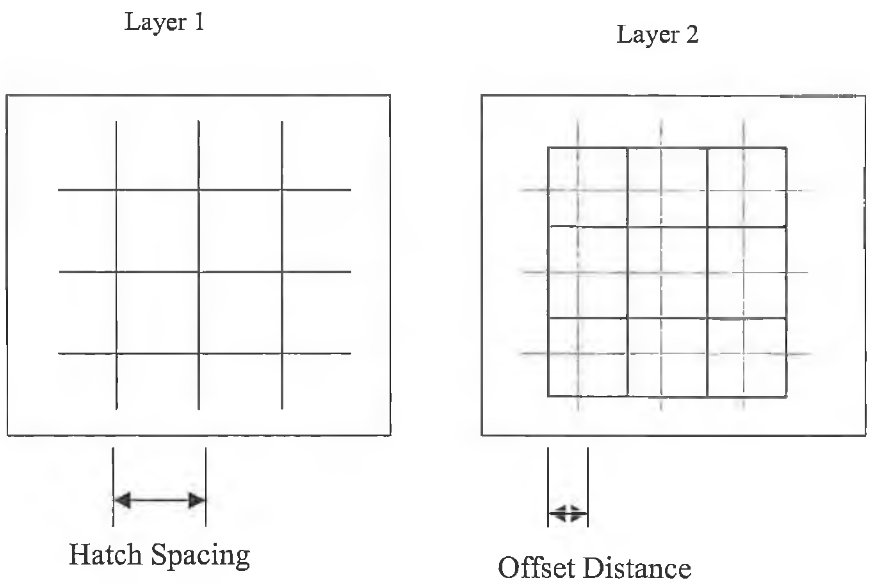
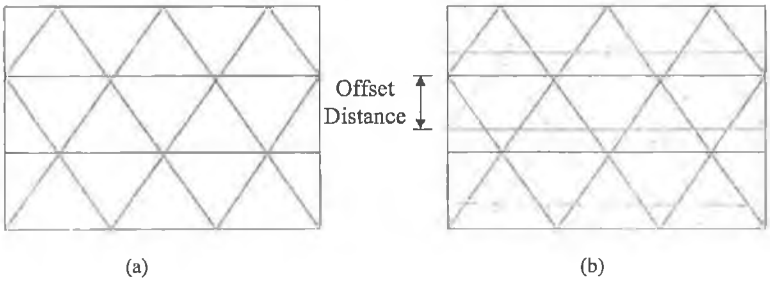


Figure 7 STAR WEAVE build style

2.3.6 Hollow build styles

(Quick Cast) The part produced in this technique is almost completely hollow. The boundaries of the layer are drawn and solidified completely before the interior. The interior of the part is filled with either squares or equilateral triangles, the squares offset by half of the hatch spacing every other layer, the triangles are offset such that the vertices of one section are above the centroids of the triangles in the previous section see Figure 8. Drains and vents must be designed to allow the excess resin to bleed out. [3, 21]



Quick Cast build style. (a) one layer of Quick Cast;
(b) Alternate layer of Quick Cast offset to centre
of the previous section

Figure 8 Quick Cast build styles

2.3.7 Fabrication

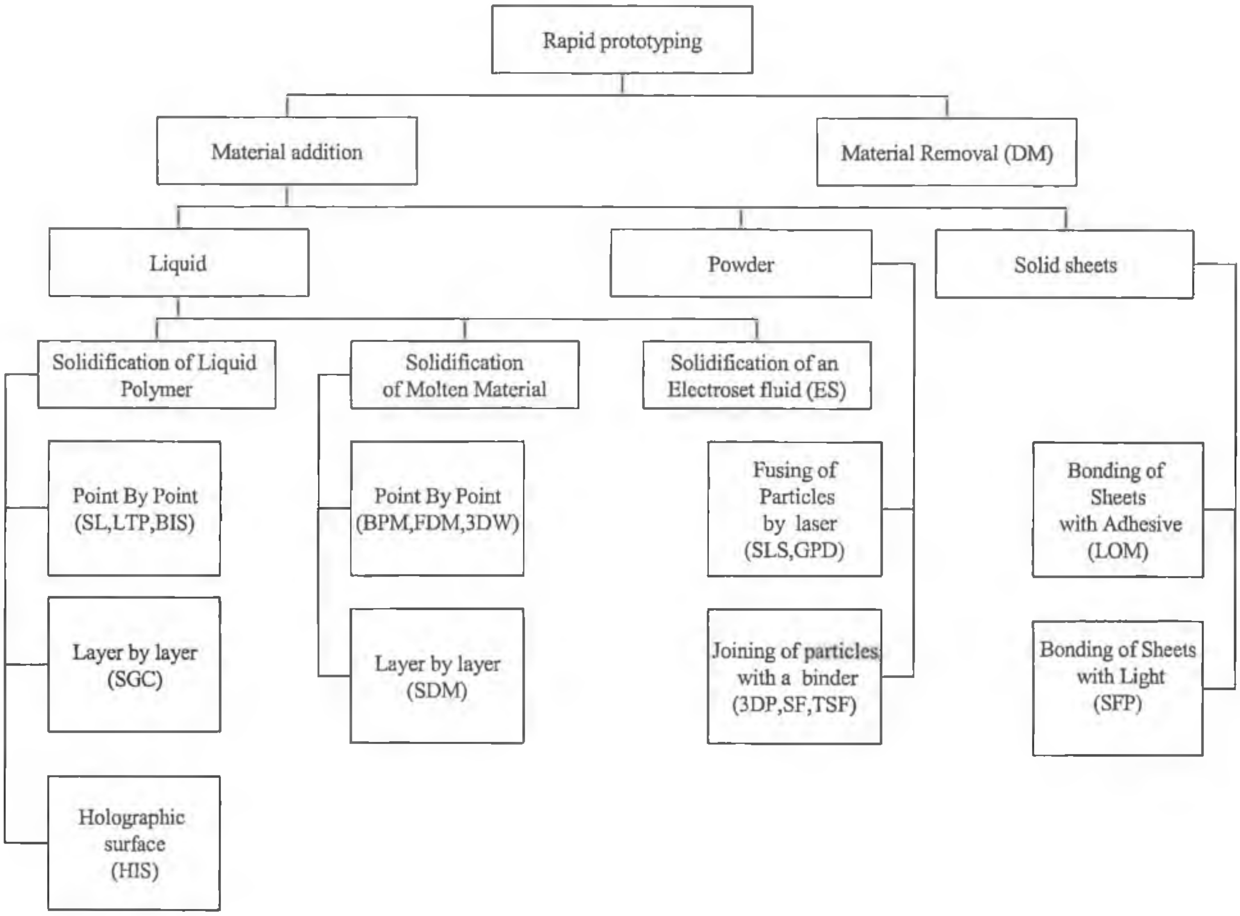
This is where the actual prototype is produced. The information for each layer is sent to the RP machine, which drives the head of the laser, extruder, etc. depending on which technology is used to fabricate the layer. Each layer bonds to the previous layer, starting from the bottom section and working up to the top until the part is complete.

2.3.8 Post Processing

In this stage the prototype is taken from the machine and any supports are removed, post processing may include curing of the photosensitive material. Some techniques require minor cleaning and surface treatment. This could include sanding, sealing, and painting to improve appearance [22].

2.4 Overview Of RP Technologies

Rapid prototyping technologies are divided into those involving removal of material and those involving addition of material. The material addition technologies may be further divide according to the state of the prototype material before fabrication (liquid, powder or solid sheets). The liquid can be a resin, which solidifies on exposure to light from a laser, electro-setting fluid, or a molten material. The powder may bond with a laser or by application of binding agents. The solid sheets may bind with a laser or with an adhesive [3]. Figure 9 classifies some RP technologies, some of which will be discussed in detail [23, 24].



SL- Stereolithography
LTP- Liquid thermal polymerisation
BIS -Beam interference solidification
SGC- Solid ground curing
HIS- Holographic interference solidification
ES- Electrosetting
BPM- Ballistic particle manufacture
FDM- Fused deposition modelling
3DW- Three dimensional welding

SDM- Shape deposition manufacturing
SLS- Selective laser sintering
GPD- Gas phase deposition
3DP- Three dimensional printing
TSF- Topographic Shape Formation
SF-Spatial forming
LOM- Laminated Object Manufacturing
SFP- Solid foil polymerisation
DM- Desktop milling

Figure 9 Classification of rapid prototyping methods (adapted from [3,7])

2.4.1 Stereo lithography (SLA)

Stereolithography is considered the most popular RP technology. It was first invented by Charles Hull [6] and introduced commercially in 1988 by 3D systems. The material used is a photosensitive liquid resin (epoxy) [3], which when exposed to an ultra - violet helium-cadmium or argon ion laser forms a polymer and solidifies.

The SLA machine consists of a platform, which is mounted in a vat of resin, see Figure 10. The platform is lowered below the surface of the resin by a layer thickness. The laser beam traces the contour of the layer, then the cross section of the model is either hatched or solidified using information obtained from the 3D solid model. Once a layer is completed, the platform is lowered a layer thickness, which is defined by the depth limit of the light absorption [6]. The resin flows over the first layer, and is left until it settles. In some machines a wiper is used to spread the viscous polymer. The laser draws a new layer on top of the previous layer, this process continues until the part is completed.

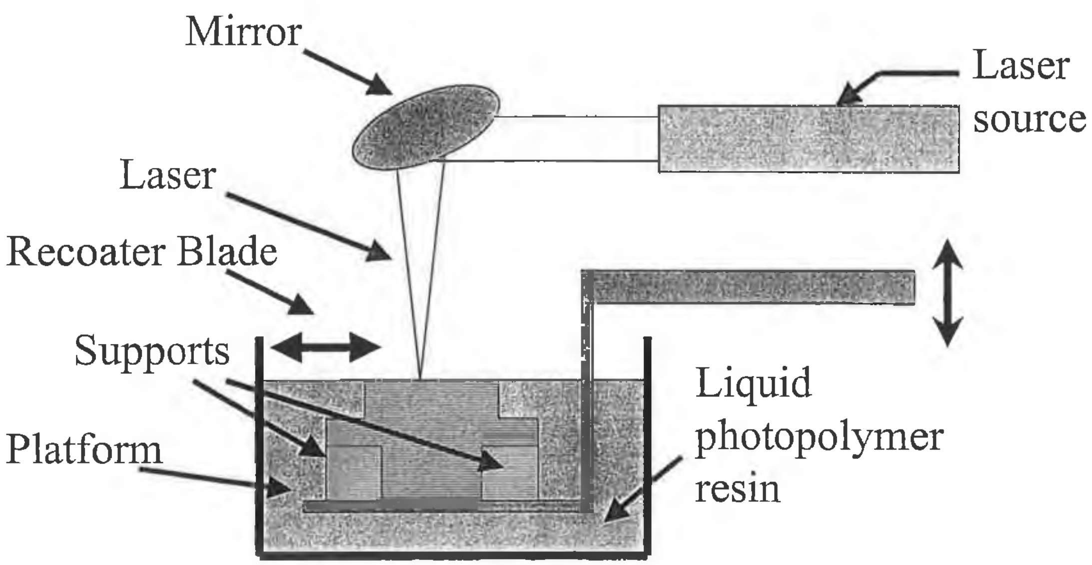


Figure 10 Schematic of stereolithography (SLA) RP process.

When the layers are finished, the part is removed from the vat drained and washed. This may take several hours due to the resin viscosity. The supports are removed and the part placed in a fluorescent oven where UV light floods the prototype to completely solidify it.

Advantages

1. The SLA machines are the most accurate machines among all current rapid prototyping machines with an accuracy of ± 100 μm. The 3D Systems introduced SLA 7000 system, which has a minimum layer thickness of 25.4 μm [6, 23, 24].

2. The model fabricated with SLA is ideal for assembly testing, function testing, visual aids, medical models and patterns for tooling.

Disadvantages

1. The material is expensive, smelly, and toxic.

2. The material must be shielded from light to avoid premature polymerisation.

3. The part may be brittle and not strong enough for high stress testing.

4. Support structures must be built for over hanging features.

2.4.2 Selective laser sintering (SLS)

The SLS was developed by Carl Deekars and Joseph Beaman at the mechanical engineering department of the University of Texas at Austin, and introduced to the commercial world in 1992 by DTM Corp [6]. In the first quarter of 2001, 3D system announced the acquisition of DTM Corporation [23].

The process starts with a thin layer of powder spread across the platform using a counter-rotating roller, and preheated to a temperature slightly below its melting point see Figure 11. The powder is sintered using a carbon dioxide (CO_2) laser of power in the range of 25-50 W, the laser beam traces the cross section on the powder surface to sinter the material. Then the platform is lowered and the powder feed chamber rises. The counter-rotating roller spreads a new layer of powder. The laser draws the new layer on top of the previous one. The sintered powder forms the part whilst the unscanned powder remains in place to support the next layer. This continues until the part is completed.

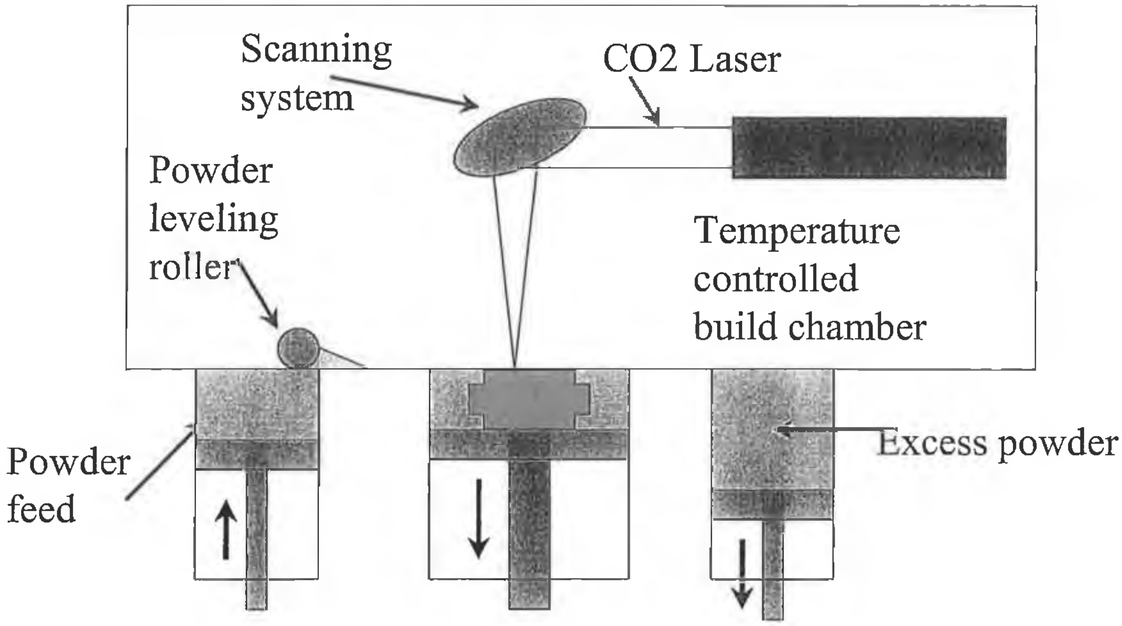


Figure 11 Schematic of selective laser sintering (SLS) RP process

Advantages:

1. A wide range of material is available for this process. Including polycarbonate, PVC (Polyvinyl chloride), ABS (acrylonirile butadiene styrene), nylon, resin, polyropane, polyurethane, investment casting wax, sand ceramic and metals [3, 6]
2. No post curing is required (except for some materials such as ceramics).
3. No support structures are needed.
4. The materials are cheaper than the material for SLA.
5. The materials are non toxic and safe as used in this process.
6. The process is considered fast compared with SLA.
7. It produces good visual representation models.

Disadvantages:

1. Parts need a long cooling cycle.
2. Each materials has its own melting point and specific heat, so the laser parameters need a different setting for each material.

3. Although this process is able to produce metallic parts the performance and accuracy are poor due to shrinkage of metal powder [25].

2.4.3 Laminated Object Manufacturing (LOM)

This system uses a roll of material which is drawn from a feed roller to a take-up roller across the top of build stage see Figure 12. The material delivery rollers stop while the material is bound to the previous layer using a hot roller, which activates a heat-sensitive adhesive. The contour of the cross-section is then cut with a laser beam that is carefully modulated to penetrate to a depth of exactly one layer thickness [3]. The excess material is cut into small rectangles and remains in place to support the next layer. The build stage drops down by a layer thickness and the material is advanced by the roller until a new layer may be cut. The width of the part is limited by the material width.

The system uses a 25-50 W CO_2 laser to cut the material, the process generates considerable smoke so the build chamber must be sealed and either a chimney or a charcoal filtration is required [26].

The waste material which has bonded to the part on the top and the bottom surface must be hatched with smaller hatches to facilitate removal, it may be necessary to stop the process to remove the material from cavities, which are too difficult to access after completing the part. It can be time consuming to remove extra material for some geometries.

Although the principal commercial provider of LOM systems, Helisys, ceased operation in 2000, Cubic Technology has been founded to support the technology, and there are several other companies providing similar technologies. A knife is some times used to cut the outline of the part and cross-hatch the waste material. Ability to bond only the required cross-section to the previous layer is used in some systems. A new online de-cubing laminated object manufacturing process can remove about 30–80% waste material during the machining process proposed [27], this process shortens the time for laser cutting and de-cubing and enables the automated production of hollow and shell-shaped parts.

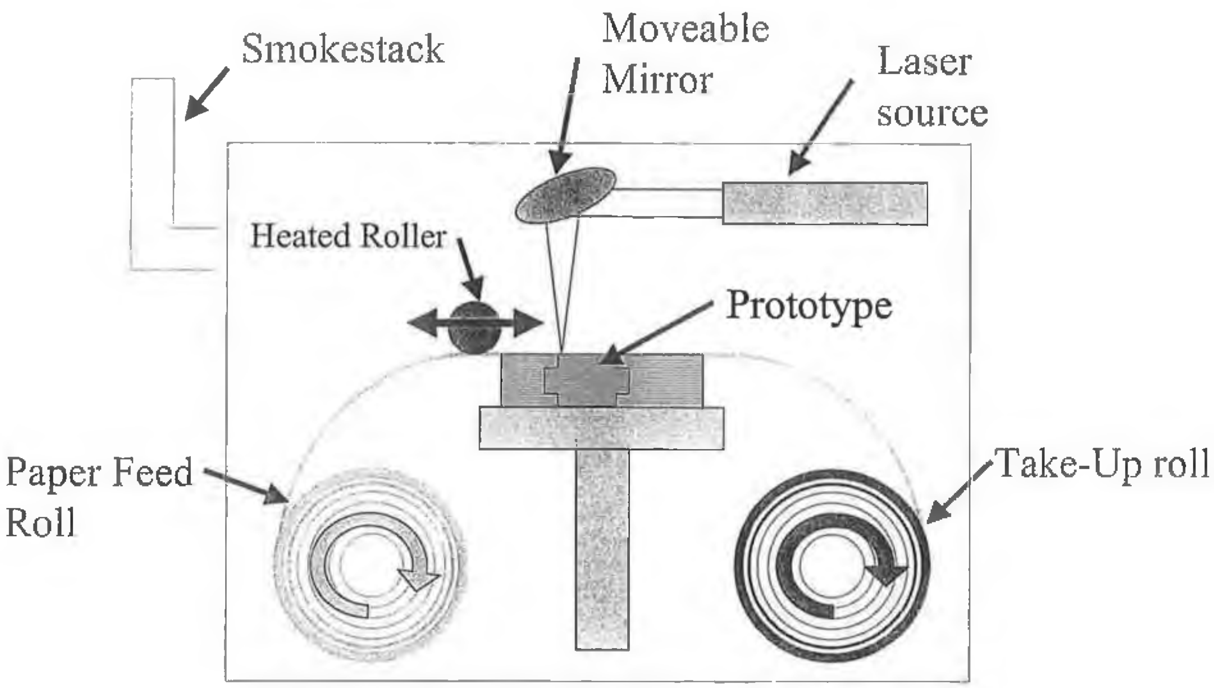


Figure 12 Schematic of Laminated Object Manufacturing (LOM)

Advantages:

1. 5-10 times faster than most of other processes, as only the contour of the part needs to be traced by the laser beam [3].
2. A wide range of relatively lower cost materials is available for this process.
3. The low internal tensions in the parts prevent distortion, shrinking and deformation [6].
4. The parts have high durability, low brittleness and fragility.
5. Very large RP parts can be produced by this process (513×559×508 mm) [3].
6. LOM materials are non-toxic and non-reactive, and therefore easy to handle and dispose [28].

Disadvantages:

1. It is difficult to make hollow parts due to the difficulty in removing the core.

2. The part accuracy is limited due to the comparably simple machine design [28].
3. There is a large amount of scrap.
4. There is a fire hazard, because of using the laser for cutting the material, which means that the machines need to be fitted with an inert gas extinguisher.
5. Finishing and sealing the parts is difficult and requires much effort [28].
6. If the part is made of paper it should be sealed with a urethane, silicone or epoxy spray to prevent later distortion, due to water absorption.

2.4.4 Three-Dimensional Printing (3D Printing)

3D Printing was developed at Massachusetts Institute of Technology (MIT) [22]. In 3D printing a layer of powder is spread on the substrate, a nozzle deposits a liquid adhesive compound onto the powder where the solidification is required. After one layer is completed, a new layer of powder is spread out and selectively glued. The process is repeated until the entire object is completed, the unbound powder, which was supporting the part is removed.

Aluminum oxide, alumina silica and ceramic powder can be used as building material. The binder material is amorphous or colloidal silicon carbide in the 3D printing system. Z Corp. introduced a colour-capable system in 2000 and this uses starch, plaster and other types of powder [22].

Advantages:

1. It is a fast technique compared to the other SLA and SLS techniques.
2. It is able to produce the items at lower cost.
3. It does not require supports.
4. The system is ideal for an office environment or educational institution [29].

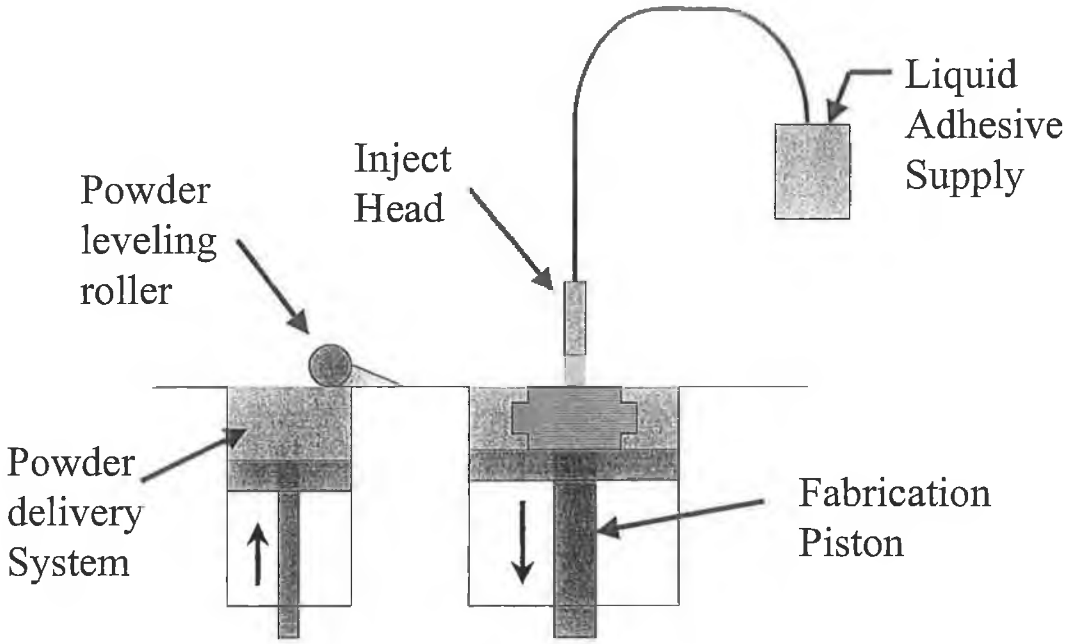


Figure 13 Schematic of Three-Dimensional Printing (3D Printing)

Disadvantages:

1. The part may be fragile and porous.

2. It can be hard to remove the excess powder from the cavities.

3. A smaller stair-stepping effect in the x-y plane as well as in z direction due to employing raster-scanning for the print head [3]

2.4.5 Fused Deposition Modelling (FDM)

Stratasya Inc. developed the FDM system, and introduced it in 1990 [6]. The system consists of a build platform, movable extrusion nozzle, and a control system, see Figure 14. The extruded material is heated in the nozzle to 0.5 °C above its melting point by a resistance heater. The nozzle traces the two-dimensional cross section of the model and extrudes the material under the control of a precision pump [6]. The material solidifies about 0.1 s after extrusion and cold-welds to the previous layers. The temperature of the previous layer has to be maintained just below the melting point of the material for good adhesion with the next layer [30]. After one layer is finished, the extrusion head moves up a layer thickness to build the next layer.

A second nozzle is used to extrude the support material for overhanging parts, in the latest FDM systems [3].

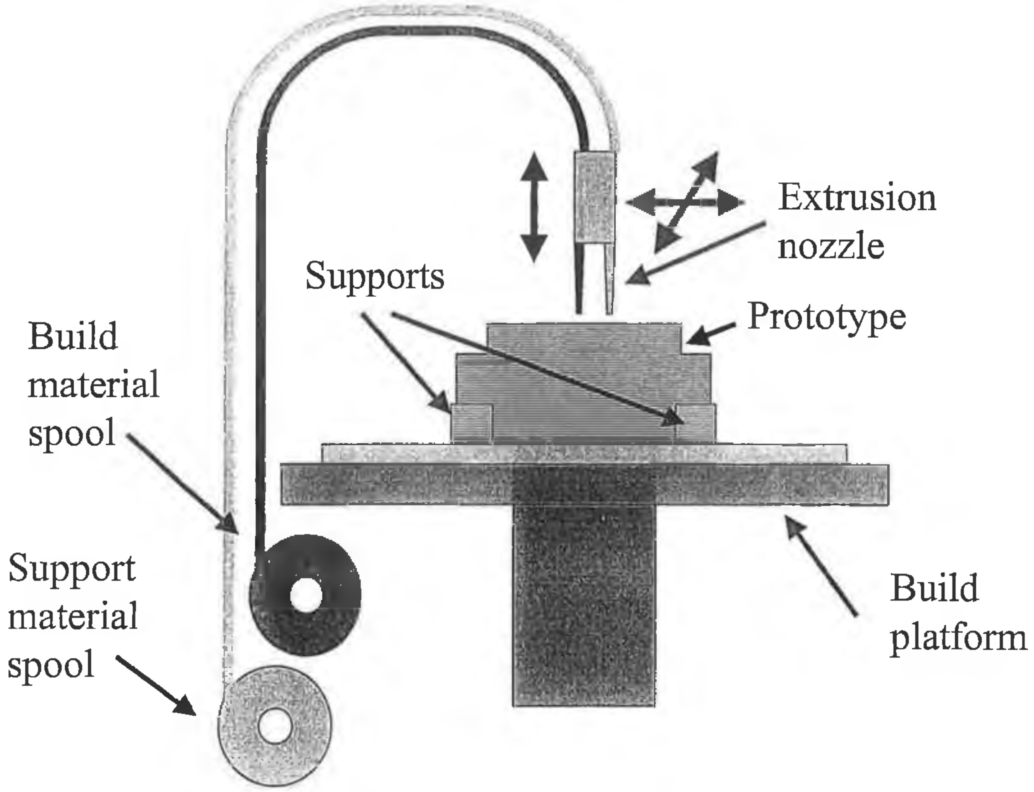


Figure 14 Fused Deposition Modelling (FDM)

Advantages:

1. FDM is considered a cheap and quick way to produce models, since the techniques it uses are simple and the materials it uses are cheap.

2. There is a wide range of material available for this system such as investment casting wax, ABS plastic, medical grade ABS, and nylon. They can also be in different colours.

3. All the materials are non-toxic, non-smelly and environmentally safe.

4. There is minimum material wastage in this method; the only waste material is from the support structure.

5. Stratasys systems can be used in any office environment without special venting or facility requirements [31]

Disadvantages:

The main disadvantages are that the accuracy of the part is restricted due to the shape of the extrusion used. A typical commercial machine has accuracy of $\pm 127\ \mu m$ and 178-365 μm layer thickness [31].

2.4.6 Ballistic Particle Manufacturing (BPM)

The (BPM) technique developed by Perception Systems injects tiny droplets of molten material from a nozzle, which hit the substrate and immediately cold-weld to the previous layer, the injection head moves and drops the material where it is required to form the layer of the object [6].

The stream of molten material is separated into droplets using a drop-on-demand system or a continuous jet. When a continuous jet is adopted, the material is injected through the nozzle, which is being excited by a piezoelectric transducer at a frequency of about 60Hz. The transducer must be located at a distance from the nozzle to avoid any damage. The disturbance at the nozzle produces a stream of small, regular droplets with uniform spacing and distance [3].

Solidscape, Inc. machine passes a milling head over the layer to make it a uniform thickness. Particles are vacuumed away as the milling head cuts. If a clog is detected, the jetting head is cleaned, the problem layer is milled off and then the process continued [26].

The Thermojet machine developed by 3D systems is a much faster operation since it deposits materials from hundreds of jets. This machine uses the modelling material itself as support, in a very fine structure, to remove this support they are simply brushed away[26].

Perception Systems Inc.machines use wax, Automated Dynamics Co. uses aluminum [6]. Other materials currently employed are tin, zinc, lead, lower than 420 °C melting point alloys and thermoplastics [3].

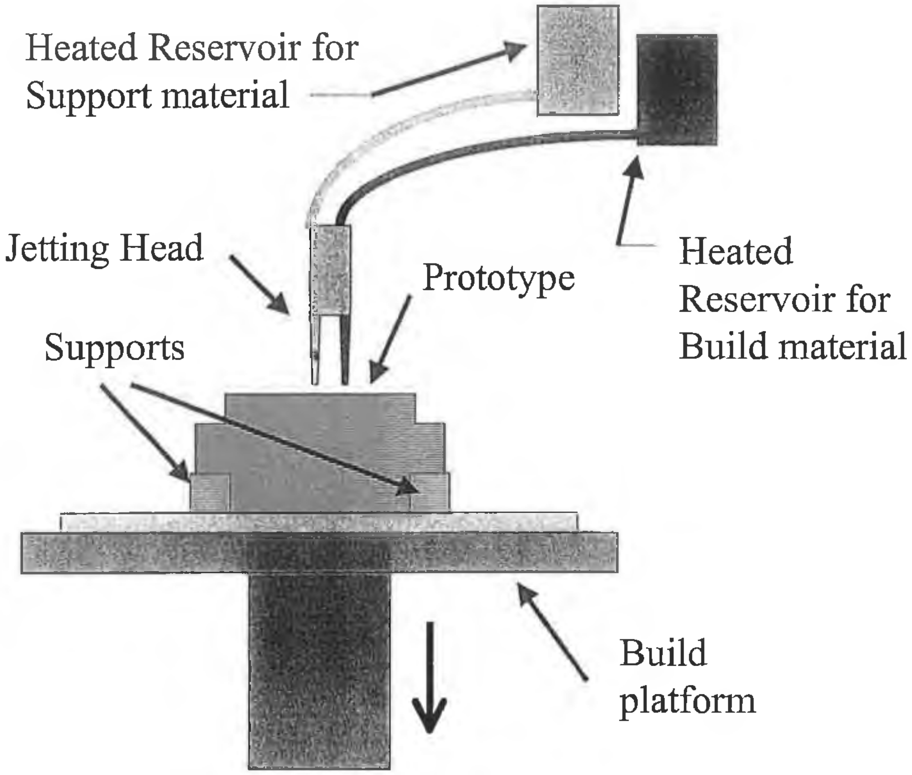


Figure 15 Ballistic Particle Manufacturing (BPM)

Advantages

1. It is cheap and environmentally safe [3].
2. It has good accuracy of ±25 μm, layer thickness of 13-130 μm
3. It is capable of a resolution of 101 μm in x-y plane, and a linear speed of 310 mm/s

Disadvantages

There is a small range of commercial materials available to use in for this system.

2.4.7 A short comparison

The major aspects taken into consideration when choosing which RP technology to use are part production time, cost and functionality. Each RP technology has restrictions imposed by cost, accuracy, materials, geometry, size and fineness of pattern [32]. Table 1 is a short comparison of the main features of the different RP systems.

	SLA	SLS	LOM	3DP	FDM	BPM
Company	3D System Inc.	DTM Corp	Helisys	Z Corporation	Stratasya Inc	
Max. Part size (mm)	500x500x 600	330 x 380 x 425	813x559 x 508	355 x 457 x 355	600 x 500 x 600	300 x150 x 220
Layer thickness μm	25.4-900	76-130	76-245	177	50-762	13-130
X-Y Resolution μm	200-250	50-70	203-254	508	245	101
Accuracy μm	±100	±51	±127	±127	±127	±25
Supports required	Yes	No	No	No	Yes	Yes
Materials	Photo curable resins	Thermoplastics (PVC, nylon, ABS, styrene-acrylonitrile), Wax, metals	Paper, nylon, Polyester, Ceramic	Ceramic, Metal	ABS, Methyl Methacrylate Acrylonitrile Butadiene Styrene (MABS), Wax, Elastomers	Thermoplastics, Wax

Table 1. A short comparison of some RP technologies

2.5 Applications

Although RP technologies are still at their early stage, a number of industrial companies have benefited from applying these technologies to improve their product development.

2.5.1 Verification and optimisation the Design

No matter how well engineers interpret the design concepts in CAD systems, it is still very difficult to visualize exactly what the actual complex products will look like. Some errors may still escape from the review of engineers and designers, with RP the prototype can be built quickly and cheaply, therefore engineers can evaluate a design very quickly.

2.5.2 Layer manufacturing

Making patterns for injection moulding is an expensive operation and, when small quantities are required, it is possible to use RP technologies as a manufacturing technique to reduce the cost and the time. In some cases parts need to be produced with internal shapes that could not be manufactured using traditional technologies. RP can be a solution in these cases [3].

2.5.3 Rapid tooling

It is possible to use some RP technologies to produce tools directly. RP parts are used as moulds for concrete, fibreglass and expanding foams. Parts made of wax or other low melting point materials may be painted with metal. The metal shells can be used for plastic injection moulding [3], RP is used also for investment casting, where the parts are coated with a ceramic slurry and then burnt out. When the investment casting wax is burnt out, this leaves a very little ash content less then 0.002% while parts made of paper in the LOM technique leave approximately 3% ash at 760 °C.

2.5.4 Marketing

Prototypes can be used to demonstrate the design concept to gain customer feed back so that the final product will meet the customers requirements [6].

2.5.5 Other Applications

RP technology has been introduced successfully in the industries of automotive, aerospace, shipbuilding, computer, toy, and consumer products. Microelectronic-mechanical systems and medical applications are also very important fields. [33].

2.6 Development In RP

The current and future primary efforts are to manufacture "functional components" and the "form/fit" parts that the majority of today's RP technologies produce. For this purpose RP processes are being developed with emphasis on materials, tolerance, software, and better process control. Many limitations associated with the RP process have been improved in recent years with the development of new materials.

2.6.1 Accuracy

There is an increasing requirement to improve the RP part accuracy to the equivalent of those produced by traditional machining methods. Surface accuracy can be defined as the deviation of the geometry from the progenitor CAD model to the part. The loss of accuracy is mainly due to (1) pre-process errors, (2) process planning errors, (3) Process errors, and (4) post-process errors [15]. These errors reduce RP product accuracy and obstruct its further applications.

1. Pre-process errors

These errors are due to the representation of the part in a CAD system for data exchange purposes. Most if not all the commercial RP machines use the STL file format as a 3-D input data for the geometry. Although STL format is the de facto standard for RP technologies, it still has many problems such as redundancy, inaccuracy, and incomplete integrity. The enclosing surfaces of the solid model are normally approximated by series of triangles (STL format), which results in chordal error see Figure 16. This chordal error leads to a non-smooth surface. To generate a STL file model, a tolerable chordal error has to be set. A small tolerance value results in an increased number of facets, increasing the file size and part build time.

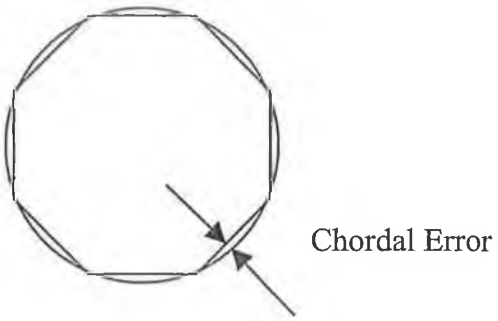


Figure 16 Chordal error between actual surface and tessellated surface

Most RP software effort focuses on geometry verification of the STL CAD model prior to part fabrication [14, 37]. The need to improve the STL format or its processing has been recognised. Many approaches have been proposed, one approach is to use other existing data formats such as IGES, HPGL, STEP and CT data; other approaches are under investigation such as NURBS and direct slicing methods [1, 34, 35].

2. Process planning errors

The staircase effect is a result of the slicing process and therefore a common source of dimensional inaccuracy in RP. The staircase effect can be measured by the layer thickness and the angle between the vertical and surface tangent.

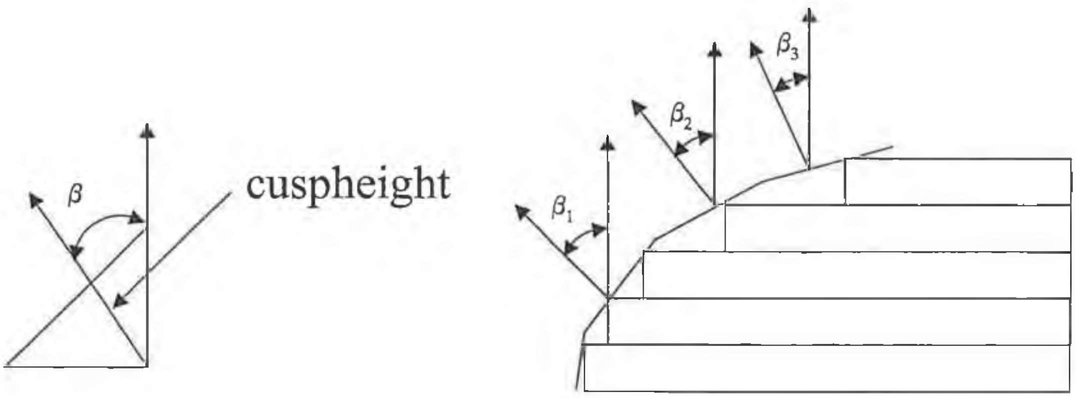


Figure 17 The stair-step effect due to layer thickness.

This error can be quantified by cusp height, which is the distance between the intended and approximated surface at each facet Figure 17, or may be represented as the volumetric deviation [36], which can be evaluated by calculating the volumetric error for each layer to give the overall volumetric deviation.

Some systems reduce the staircase effect by optimising the build direction for each layer. Layers are then added at various angles using a five axis tool head [37] or smoothed through staircase machining [38].

Most RP systems deposit material in only one direction, and reduction of the staircase effect can be achieved by slicing the part using a smaller layer thickness causing longer RP fabrication time. An adaptive slicing approach improves the surface quality and shortens the build time for RP see Figure 18. The variable layer thickness produces very thin layers, especially when slicing objects having curved surfaces, so that the build time may therefore still be very long [39]. Local adaptive slicing improves the surface quality and shortens the build time, using this method only the skin regions have thin layers to ensure a smooth part surface. The internal areas will be processed with the maximum allowable layer thickness of a particular process [5, 40].

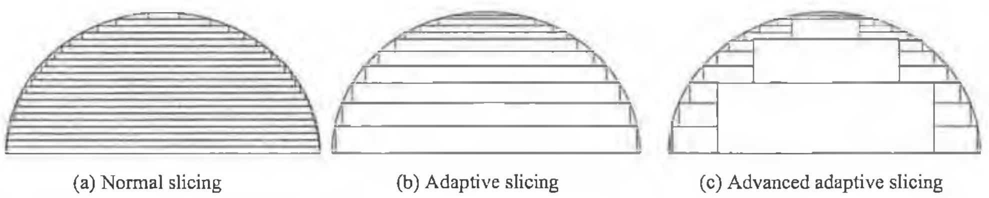


Figure 18 Methods of slicing to reduce the staircase errors

3. Process errors

Process errors are mainly due to laser delivery mechanisms in SLA and SLS, the induced angle with the part surface and the beam width. The beam width is not constant from machine to machine and not constant even on the same machine over time [34]. Other process errors can occur because of the speed of recoating the resin and the flatness of the resin surface. In FDM the width of the material delivered and its temperature can result in errors. In SLS and 3DP, the flatness of the powder spread and its density and different parameter set-ups will generate different machining accuracy and build time.

A better laser beam control mechanism and beam width compensation software has been used, which reduces the error to a minimum in SLA and SLS [34].

4. Post-process errors:

Post-process errors include shrinkage and warping errors. Shrinkage errors are mainly due to solidification of the part, which causes non-uniform volumetric changes and distortion [41]. The earlier resins available from 3D Systems Inc. are primarily limited to the acrylate base resins with relatively large shrinkage (5–7% in volume), causing severe distortions of the finished parts. Many researchers are striving to develop new resins that offer low shrinkage and high dimensional stability. 3D Systems and Ciba Geigy Corporation introduced an Epoxy resin called XB5170 which has a small shrinkage of 2–3% in volume [34]. Warpage is error caused by uneven distribution of heat energy and resultant binding force [37].

Finite element analysis has been used to predict distortion of parts during build using different deposition strategies. The modeling predicts how material properties vary with the deposition strategy, and how changing build parameters affect residual stress in the part [19, 37, 41].

2.6.2 New Materials

The availability of materials is one limitation of rapid prototyping technology. Commonly materials used in present RP systems are polymers, paper and ceramic [33]. The properties of these materials in many cases are far from those required in the final products. The introduction of non-polymeric materials, including metals, and composites would allow RP users to produce functional parts. Several groups are working on the direct deposition of metals to form final objects [42, 43]. At least four techniques are under investigation: inkjet-based, weld deposition, masked deposition and laser fusing [44].

2.6.3 Increased size capacity

The size of parts that can be built from the most RP machines is 0.125 m^2 or less. Large parts must be split into a few smaller parts to build them separately in RP systems, and then assembled together by hand. Several large prototype techniques are being developed to remedy this situation. The most fully developed is Topographic Shell Fabrication from Formus in San Jose, CA. In this process, silica powder is congealed selectively with paraffin wax to build the mould, the mould is then used to produce fibreglass, epoxy, foam, or concrete models up to 3.3m by 2m by 1.2 m in size [45].

2.6.4 Build-time

Build-time can be defined as the time required for building a physical part. In SLS and, SLA the build-time depends on the total recoating time consumed between layers and the laser scan time used at each layer, and both of them are functions of part size and geometry [15, 33]. Rapid prototyping machines are still slow by some standards. By using faster computers, more complex control systems, and improved materials, RP manufacturers are dramatically reducing building time. 3D System introduced its SLA7000 machine, which can produce models three times faster than previous SLA machines [23].

2.6.5 Multiple material objects

Some RP machines have the capability to fabricate multiple material objects (FGM). To fabricate a multiple material object, a very complicated process is employed, first the material has to be represented in the CAD design, the material information has to be transferred to a STL file, the processor has to slice the STL file and find the areas for each material [46]. Some papers proposed a scheme for representing multiple material objects in a CAD system. A material tree of the object is built in the CAD system's data structure. Extracting information from this material tree, and outputting a modified version of a STL file format to the RP machines could allow fabrication of multiple material objects [5, 46]

2.6.6 Extension the Applications of Rapid Prototyping

As RP technology has been introduced successfully in many industrial applications, a new trend has also developed in other areas of work. Sculptors are beginning to use RP, as a method of producing complicated structures. Producing jewellery is another field in which RP technology is being used. Medical application is another very important field of application [20]. Now human organ models can be produced by means of using RP technology and medical digital imaging systems. As the machinery required becomes cheaper and the range of materials and processes increases RP is likely to become a method of manufacturing [22].

2.7 Computer Aided Design (CAD)

Computer Aided Design is defined as using the computer to assist in creation and modification of a design. The operator uses the input device such as a mouse, key board, digitiser tables, joy stick, or light pen to specify the points and lines on the display screen. The function menu assists the user in manipulating these simple entities to build a complex geometry. The graphic system allows the user to move, rotate, flip, magnify, mirror, copy, and erase entities. The frequently used drawing can be stored in a library and recalled instead of redrawing them each time [2, 47].

When CAD systems appeared in the late 1960's they were working only in two dimensions, their capabilities were improved in early 1970s to include three-dimensional wire frame and surface modelling. Wire frames contain only information about part edges and corners, surface models define the outside envelop of part geometry. By the mid-1980s all major CAD products had solid modelling capabilities, solid modelling allows the computer to determine the volume that is included within the object's bounding surface, moments of inertia, centres of gravity, and other mass properties can be computed.

CAD systems increased design accuracy, consistency between drawings, and improved the drawing speed. The greatest improvements were experienced in tasks where drawings are changed frequently or which contain repetitive or standard details [2, 47]. One of the greatest benefits of CAD is using the geometric data to perform other functions in computer aided engineering and in computer aided manufacturing, this reduces the time and the errors caused by redefining the geometry from scratch in the other systems.

2.8 Computer Aided Manufacturing (CAM)

Computer Aided Manufacturing is defined as a technique of using a computer and supporting processing software to actually produce the parts on the factory floor. Factory equipment can include robots, multiple-axis machine tools, and programmable controllers. These devices often are grouped in flexible manufacturing centres to produce different parts.

Numerical control (NC) is the most mature area of CAM, it is a technique of using programmed instructions to control a machine tool that mills, cuts, punches etc. Instructions were originally stored on punched paper tapes or magnetic tapes. In Computer Numerical Control (CNC) a dedicated mini computer stores part process data and controls the machine. In the distributed numerical control (DNC) systems instructions come from a centralized computer via net work or direct connection.

Programming of robots is another area of CAM. Robots perform different tasks such as welding, assembly, carry equipment and parts around the shop floor or moving workpieces for NC machines. CAM extend as robot capabilities to more advanced off line programming, in which robot instructions are provided by a computer, which automatically determines motion paths and grip points [2].

2.9 Computer Aided Design and Manufacturing CAD/CAM

Writing NC programs manually is a time-consuming and error-prone process requiring an experienced programmer to write instructions directly from engineering drawings, run the program on an actual machine tool, and refine it several times until it works properly. Now the computer itself can generate NC instructions based on geometric data from the CAD database, plus additional information supplied by the operator. Many systems have this capability built into their software package. In fact CAD/CAM software usually refers to a CAD package with an NC programming feature built in [2]. In some systems the CAD/CAM software tests the program in a simulated machining process, the software will note and report programming syntax errors before execution and will supply diagnostics. Once a program is syntactically correct, the computer will simulate execution of the program and will construct a drawing of a machined part. When the satisfactory program is achieved, the software will issue the program to a CNC machine for execution and can store the program on disk for future production runs [48].

2.10 Principle Of Numerical Control

In numerical control machines the control systems read the programme designed to produce a part, without human operators. The program contains commands to direct the motion of the cutting tool or movement of the part against a rotating tool or to change the cutting tools.

2.10.1 CNC Program Structure

The CNC program contains of one or more blocks, each block contains one or more words, and the word made up of a letter address (X, Y, Z, R, etc.) followed by a value, see Figure 19 [49,50].

The machine control executes each block in turn. The words in a block are executed in a specific order. For example an M code instruction is executed before any axis movement in the block. [49, 50, 51]

2.10.2 G-Codes

G codes specify the preparatory functions. They prepare the machine for what to do next. [49] There are two types of G commands modal and non-modal. Modal commands come in groups, for example G17, G18 and G19 are one group. Only one code in a group may be activated at any time. Programming another code in that group switches to another mode. The non-modal commands affect only the program block in which they appear, see Appendix A [50, 51]

2.10.3 Absolute and Incremental Mode

There are two methods of entering new positions into a CNC program, One is relative to the current Datum or Zero Point, called an absolute mode, and controlled with G90. The other relative to the current tool position called incremental mode and controlled with G91. G90 and G91 are group modal and will be effective until the next G is programmed.

```
Operation List    POST: Alpha Standard 3 ax Mill
------------------------------------------------
OP 1   CONTOUR POCKET   TOOL 1   FLAT - 2MM
     EFFECTIVE DIAMETER 2, WIDTH OF CUT 2
     Feed Distance: 8494.7   Time for OP 1: 10m 40s
------------------------------------------------
Total Feed Distance ...................... 8494.7
Tool Change Time .......................... 0m 10s
Total Time ............................... 10m 50s
------------------------------------------------
Material: Mild Steel Roughing
Use Emulsion Coolant
------------------------------------------------
START
'(NC2.CW)
```

Comments from Alpha-CAM

```
%------------------------------------------------------------------------------------Start of the code

N10 (PROGRAM PRODUCED  - 19 JUN 02)
N20 G90 G71
N30 G40 G80
'(OP 1   CONTOUR POCKET   TOOL 1   FLAT - 2MM)
'(EFFECTIVE DIAMETER 2, WIDTH OF CUT 2)
N40 T0101 M03        'Select tool and offset
N50 S4000 H01 M06      'Next tool is 00, Next XY is 54., 54.
N60 G0  X54. Y54.   <------------------  Rapid linear motion
N70 G43 Z5. H01 M09
N80  Z2.
N90 G1 Z-2. F800   <------------------  Linear Interpolation G1 with the feed rate F
N100 Y56.
N140 X52. Y56.
N180 X52.
N1170 G2 X20. Y92. R2.   <----------  Circular interpolation G2 using radius method R
N1180 G1 X90.
N550 M98 P1              'CALL SUB 1
N560 G0  Z30.
N570 M09
N580 M30
:1                    'BEGIN SUB 1
N590 G1 X11.174 F800
N730 X78.375
N740 Y59.413
N760 X46.174 Y54.413
N830 X31.174
N840 Y39.247
N850 X68.375
N860 Y49.413
N870 X41.174
N880 X36.174 Y44.413
N890 Y44.247
N900 X63.375
N910 Y44.413
N920 X36.174
N930 M99                 'END SUB 1
%
```

Sub program get called every time the tool moves a round the pocket

Figure 19 CNC program generated in AlphaCAM software

2.10.4 Motion Commands

There are only four commonly used commands to determine the motion of CNC machines G0, G1, G2, and G3. G0 is rapid interpolation, G1 is linear interpolation with the feed rate in F, G2 is circular interpolation in clockwise direction, and G3 is circular interpolation in counter clockwise direction.

All motion commands are modal commands, meaning they remain in effect until changed or cancelled [49,51]. Below an explanation of G0, G1,G2 and G3 is presented.

1. Rapid Linear motion G0:

This command is used to position the CNC machine close to the workpiece. In this mode the tool will move at the fastest possible rate to the programmed point.

2. Linear Interpolation G1:

In this mode the tool will move along a straight line. The control moves the tool to the programmed point at feed rate defined by the word F in the same block.

3. G2 and G3 Circular interpolation:

In this mode the tool will move along a circular arc with a specific feed rate, two axes will always move together in the current plane. For most machines G2 represents clockwise motion and G3 represent counter-clockwise motion. There are two methods of determining the radius of the arc. Either the radius is programmed using the R command or the centre is described using the I,J and K command.

1. <u>I's, J's and K's method</u>: Some older CNC controls do not allow the programmer to specify circular motion with a radius command. They require the programmer to specify the location of the centre point of the arc. The most common method of using I, J and K in circular commands involves knowing the distance and direction from the start point to the centre of the arc

   I: is the distance and direction from the starting point of the arc to the centre of the arc along the X-axis.

J is the distance and direction from the starting point of the arc to the centre of the arc along the Y-axis.

K is the distance and direction from the starting point of the arc to the centre of the arc along the Z-axis. [49]

2. Radius method: The most common and simple way for specifying circular motion on current controls is by specifying the radius of the arc along with the end point see Figure 20. The control will automatically figure out how to make the circular motion.

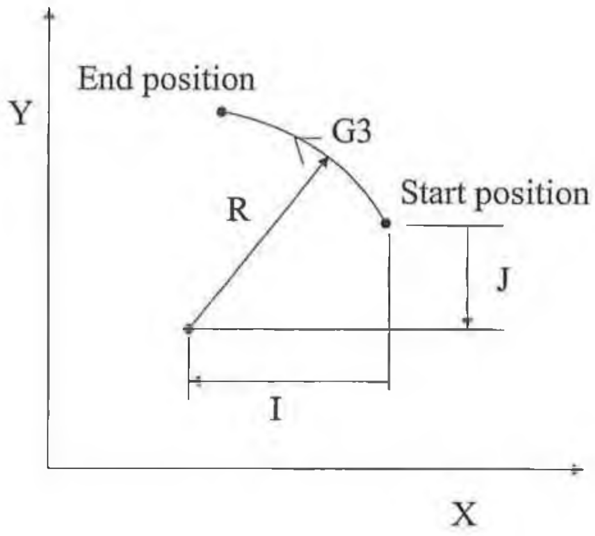


Figure 20 Illustration of variables used in circular interpolation

Chapter 3 Overview of the Wax Droplet RP System

This system is previously used by Hong Ph.D[52], Ibrahim, M Eng [53], and Bruce Stirling B. Eng [54] as RP technique. The main components are the PC controlled precision manipulator and the deposition system, see Figure 21.

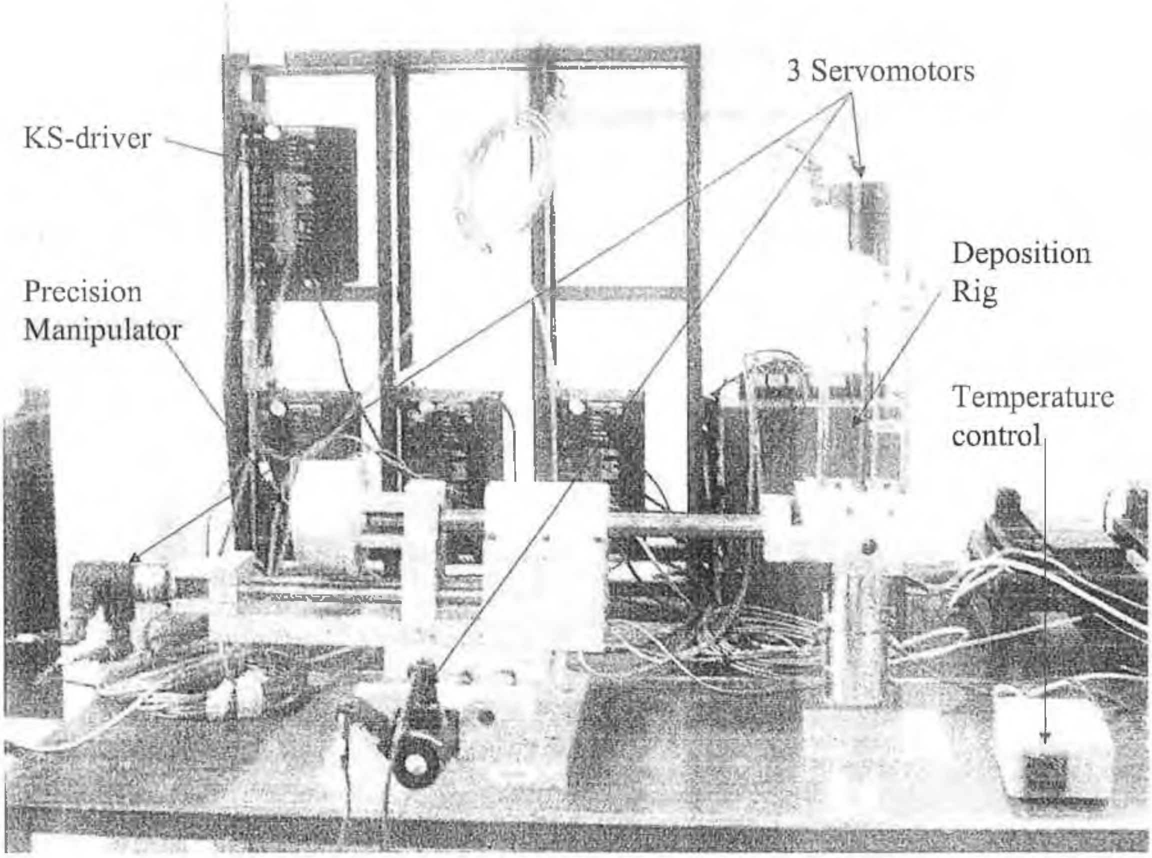


Figure 21 Wax Droplet RP System

3.1 Deposition system

The aluminium deposition chamber is the basic of this rig. It is designed to deposit a approximately 100ml per fill, Figure 22.

The rig consists of three main areas. They all combine to create the deposition system. The areas of RP deposition system are as follow:

a. Deposition Chamber (aluminium)

b. The support rig consists of two plates and two linear guides to situate the servo-motor, lead screw and lead screw nut to transmit the power to linear movement. A flexible coupling is located between the motor and the lead screw.

3. Abound heating element with mica insulation is clamped the heating chamber
4. The plunger-head aluminium has a 'O' ring seal Nitrile.

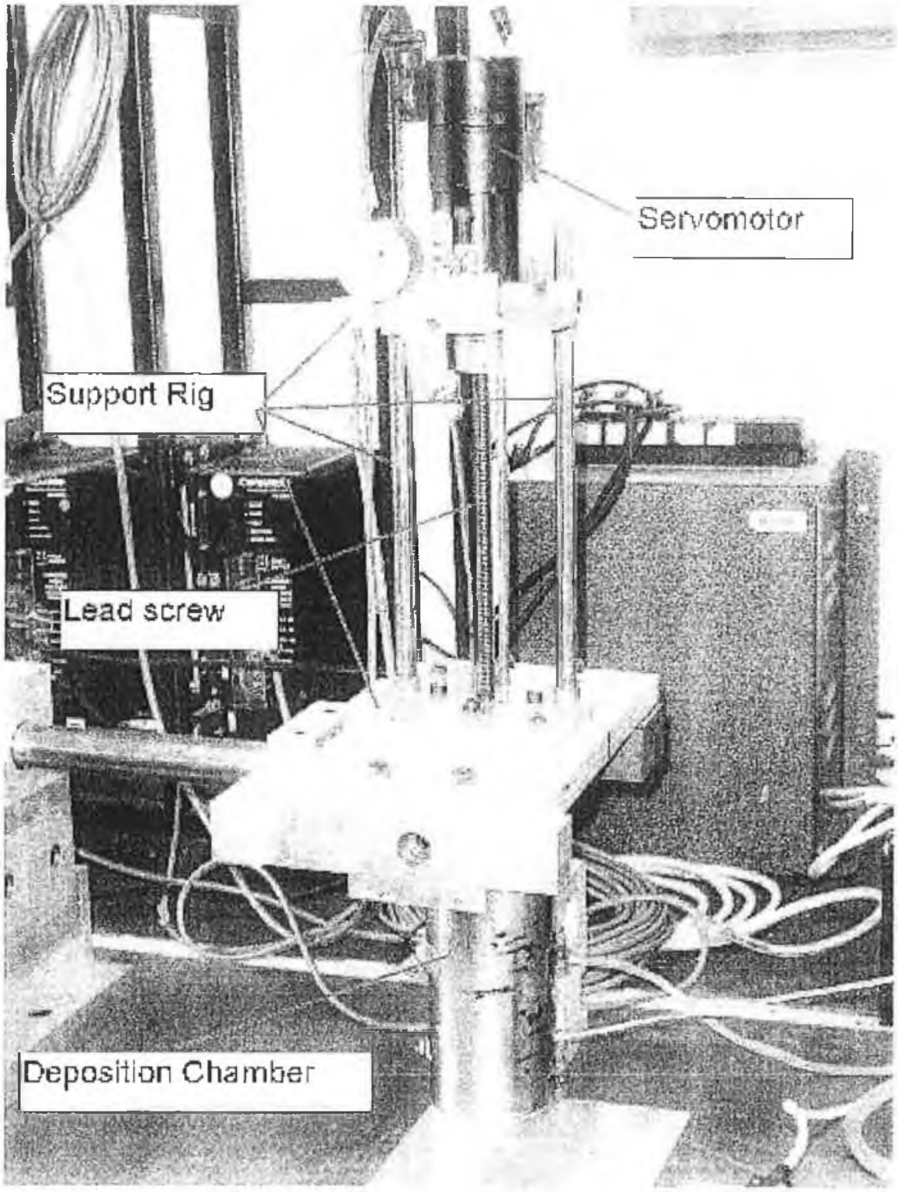


Figure 22 The components of the deposition system

3.2 Precision Manipulator

The precision manipulator provides the motion for the wax droplet system. It has two linear motions in x and y directions. The manipulator consists of a PC23, KS drivers, a.c. brushless servomotors, gearbox, lead screw and lead screw nut to transmit the power to a linear movement. A flexible coupling is located between the motor and the lead screw and two linear steel guides shafts for each axis, see Figure 23.

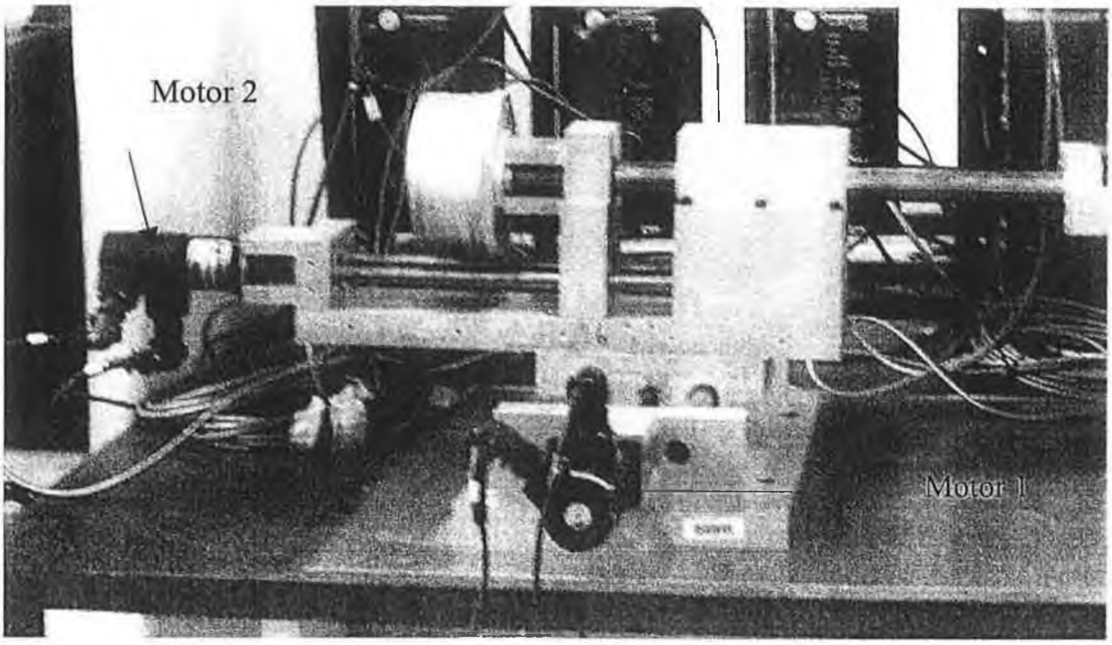


Figure 23 Picture of Precision x-y manipulator system

3.3 Wax RP System Operation

The deposition system operates by heating the cylinder, which contains the wax. A plungerhead, which fits within the deposition cylinder, is attached to the lead-screw. The system performs the deposition of one droplet of wax using the servomotor, which drives the plungerhead to deposit a single droplet and then retracts to hold the wax back in the nozzle. The deposited droplet solidifies on a receiving platform. The pressure within the chamber is kept constant by compensating the reduction in wax volume by only retracting the plungerhead a position which matches the volume of wax deposited. The resolution of the motor is very fine. Each revolution of the lead screw corresponds to 1.5 mm linear motion to 5000 motor controlling steps. The axial movement for one step is therefore 0. 3 μm, backlash is one of limitation for this precise result.

3.4 Elements Of Control

Within the project there are four elements of control, these are:

a. The control of the X-Y movement,

b. The deposition control, and

c. The heating control.

These are each very important and all influence the final output.

3.4.1 Control of X-Y Movement

The Compumotor™ PC23 is a microprocessor based indexer linked to a card in the PC. It receives acceleration, velocity and position information in ASCII format written in X language from the C++ program. The indexer then writes to an external adapter box to control the various motions. It has the ability to control up to four axes. In this application it used to control the X-Y motion and the deposition unit or Z motion are controlled. Move commands are then generated in the form of motion profiles, and then sent to the external drive units in the form of step pulses as a rate of 500kHz. The PC23 gives feedback on the positions of the axis when individual motions have been completed, see Figure 24 [54].

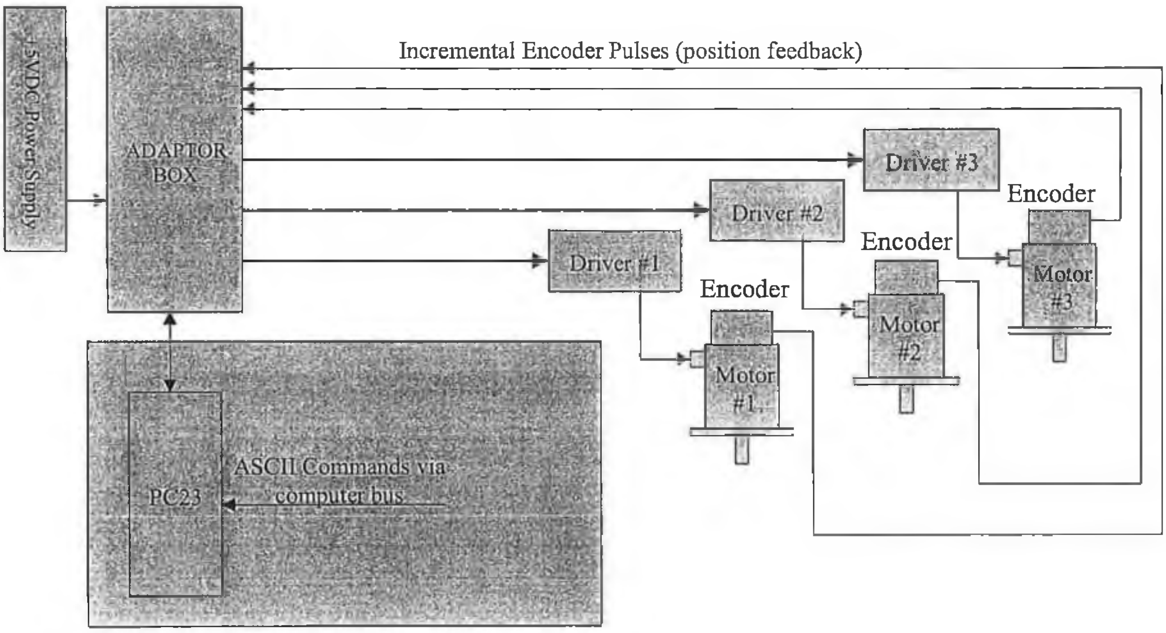


Figure 24 Interface Systems between the PC and the motors.

3.4.2 Deposition Control

The deposition control uses the same controller unit, which controls the X-Y movements. The deposition chamber is held at a pressure that is less than that of the atmosphere outside. This can be assumed, as the seepage of wax from the chamber is much greater when the plungerhead is in situ than when the plunger is out of the chamber. The basis of the deposition control is plunging and retracting movement. This allows a single droplet of wax to form and drop from the nozzle of the chamber on the forward plunge generated movement. Then the retraction of the plungerhead causes the low-pressure within the chamber to suck the excess wax back into the chamber. Thereby allowing the controlled deposition of wax droplets from the chamber.

3.5 X language and Position modes

In X language there are three positioning modes that can be used to manipulate the motor, see Appendix B for more commands. The three modes are normal, alternating, and continuous.

3.5.1 Normal (Preset) mode

Preset moves can be selected by putting the PC23 into normal mode using the MN command. Normal mode allows positioning of the motor in incremental moves or absolute moves.

a. **Incremental moves:** allows positioning the motor in relation to the motor's previous stop position. Incremental movement is selected using the Mode Position Incremental (MPI or FAS Ø) command. This is the default (Power-up) positioning mode.

1. **Absolute moves:** allows positioning the motor in relation to a defined zero reference position. Absolute move can be selected using the Mode Position Absolute (MPA or FASA1) command. The current position is set to be absolute zero reference point by issuing the Position Zero (PZ) command, or by cycling the power to the indexer. Issuing the Go Home (GH) command moves the axes to their absolute zero position. The PC23 retains the absolute position, even while the unit is in the incremental mode.

3.5.2 Alternating Mode

In this mode after issuing the Go (G) command, the motor shaft rotates to the commanded position, which corresponds to the value set by the "D" command. And then retraces its path back to the start position. The shaft continues to move between the start position and the command position. The motor stops immediately when the "S" command is issued. However if SSD1 command is issued before the G command, then when S command is issued the motor completes the cycle and stops at the start position see Appendix B.

3.5.3 Continuous Mode

In this mode when a G command is issued the motor continues to rotate in a constant movement for a period of time rather than a fixed distance. It can be synchronized to external events such as trigger input signals. Velocity and acceleration can be changed while the motor is in continuous motion, by issuing a new V and A command followed by a G command.

Chapter 4 Development Of The System

This research is aimed to improving the Wax Droplet RP System by developing a universal user-friendly software package, which is capable of fabricating different shapes without editing the control program for each different part. Three programs were developed to update the existing system CAD/RP, CNC/RP and CAM/RP, see Figure 25.

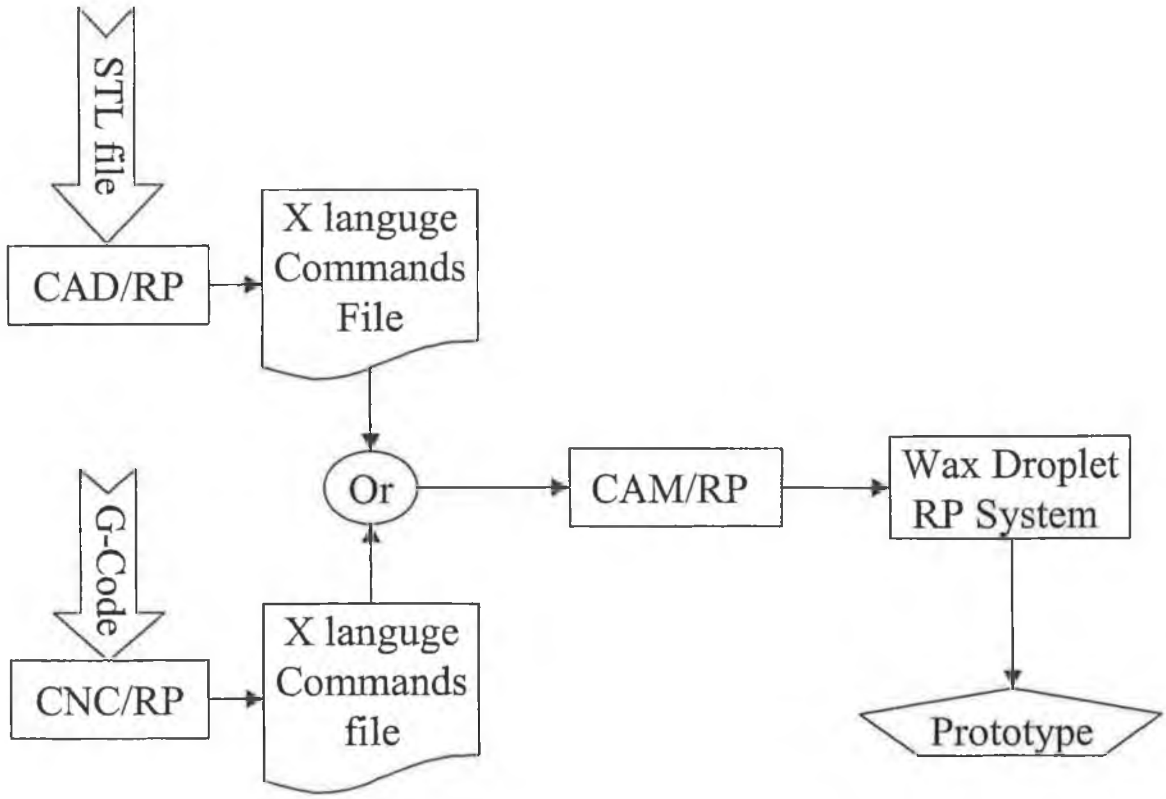


Figure 25 Flow diagram for RP operation

CAD/RP is the traditional method in RP, it is designed to generate instruction commands for the PC23 using STL files, the solid model has be designed in a CAD environment then exported to STL file format. CAD/RP imports this file and generates the instruction commands to build the prototype.

CNC/RP is a new method for RP, and generates the instruction commands for the PC23 from G-code. The G-code for the required model is generated in AlphaCAM, or any CAM software, and then saved as a text file, CNC/RP imports this file and generates instruction commands to build the prototype.

CAM/RP is the program, which controls the PC23 indexer by transmitting a sequence of commands to the unit using the correct communication protocols to ensure reliable operation. It is a modified form of the previous motion control software, it is customized to read the pre prepared instruction commands file see Figure 26. This file is output from either the CAD/RP or CNC/RP software. CAM/RP can be used in stand-alone mode to transmit any prepared set of instruction to the PC23, or used directly from within the other two programs without any extra input from the user, see Figure 25.

```
"LD3 1V1 1D-6666 1G 1P "
"LD3 3V1 3D-30000 3G 3P"
"LD3 3V5 3D29979 3G 3P"
"LD3 2V1 2D-66667 2G 2P "
"LD3 3V1 3D-30000 3G 3P"
"LD3 3V5 3D29979 3G 3P"
"LD3 1V0.7 1D471 1G 1P  2V1 2D-4714 2G 2P "
"LD3 3V1 3D-30000 3G 3P"
"LD3 3V5 3D29979 3G 3P"
"LD3 1V0.9 1D6592 1G 1P 2V1 2D-990. 2G 2P "
```

Command string sent to motor 1 to move in X direction

Command string sent to motor 3 to deposit the wax, and then retract

Command string sent to motor 1&2 to move in X &y direction

Figure 26 X language commands Output from CAD/RP and CNC/RP

CAD/RP, CNC/RP are user-friendly programs were developed using visual basic programming language, which is an application programming tool designed specifically for Microsoft windows. Visual Basic provides a powerful and flexible environment, enabling rapid windows application development. It provides an ability to write programs for a wide range of applications, with minimal effort, and significantly reduces the complexity of writing Windows applications [55]. CAM/RP was developed using C++ programming language, which is a powerful and flexible language, it has the capability to read and write digital data to the I/O bus of the personal computer [52, 54].

4.1 Development of CAM/RP software

The main task for this software is to communicate with the PC23. To operate the PC23 with X language commands, the software has to have the capabilities of reading information from and writing data to I/O bus of the personal computer.

Communication with the PC23 involves two pairs of registries. A register refers to a temporary storage area for holding one character. Data transfer to and from the register takes place one character at time.

The motion control commands and responses are transferred through the input data buffer (IDB) and output data buffer (ODB) at the indexer's based address 300Hex. Interface control commands and status information are transferred through the control byte (CB) and status byte (SB) at one address location above the base address, 301 Hex.

The ODB and SB are read-only registers. The IDB and the CB are write only register. Compumotor™ provides a sample read and write routines that access the computer's I/O bus.

X language commands are strings of ASCII characters. Passing a command to the indexer requires transferring each character in the command one a time. Each character transfer requires that the sender notify the receiver that a character is ready, and that the receiver notifies the sender that the character has been received. The notification process involves setting or clearing control bits (flags) SB and CB registers.

Control Byte CB flags allow the program to signal the PC23 with messages. The status Byte flags allow the host program to report the operation conditions such as if axis # 2 is moving or not.

The PC23 indexer is designed to operate motor axes in a fashion largely independent of the computer, requiring only a small number of high level commands and interaction. The interaction is almost in the form of characters and strings. This requires knowledge of string handling in the programming language. The program must include subroutines or procedures to do the following:

1. Reset the indexer

2. Send a command string to the indexer.

3. Receive a character string from the indexer.

Hence the PC's higher execution speed cannot be slowed down using the control program, the routines for sending commands to the indexer and receiving responses from the indexer must be changed to solve this problem. The initial routines had a particular number of loops for communicating with the indexer. The revised routines will continue to wait until the indexer gives a response.

In previous research the PC23 instruction commands were calculated manually and hard coded within this program [56]. This means the operator has to find the deposition positions for each droplet manually, then construct the move command for each droplet, and then insert these instructions into the motion control program. The program has to be compiled each time these instructions are changed.

CAM/RP is a modification for the motion control software, which is customized to read the pre prepared instruction command file line by line, it sends each instruction to the PC23, and the movement is confirmed by feedback on the positions of the axes when each motion has been completed before the next line is read.

The advantage of using CAM/RP that it dose not need to be compiled for each prototype, also it can be run from CAD/RP or CNC/RP which makes these systems work in a user-friendly fashion.

4.2 Development of CAD/RP software

CAD/RP is the traditional method in RP, where the model is designed in a CAD environment and then translated to an STL file. Most commercial solid modelling software, such as Mechanical Desktop or PRO/Engineer, can export data to an STL file. The CAD/RP software was designed to generate control commands for the PC23 to build a prototype from a CAD design. Figure 27 illustrates the entire available commands and algorithms in the developed CNC/RP software.

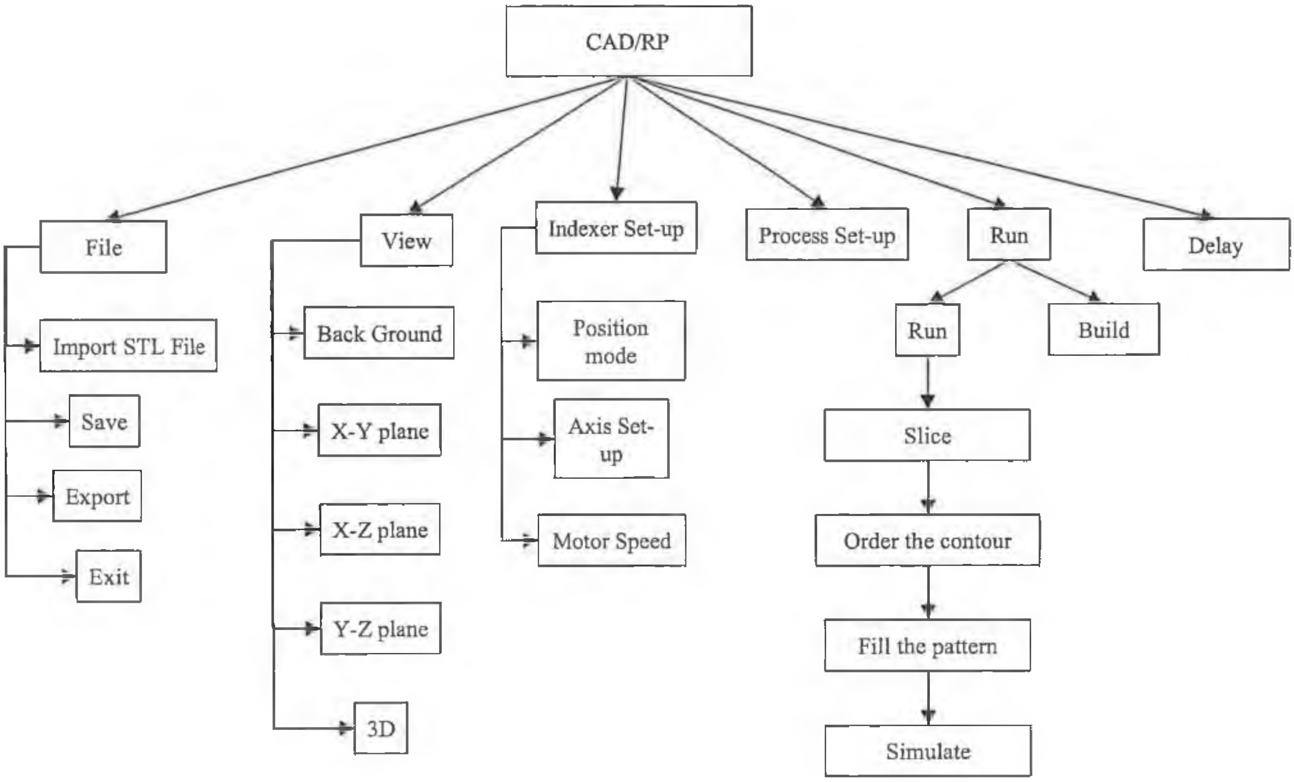


Figure 27 Structure of the developed CAD/RP program

When the CAD/RP software starts to execute it provides a single document graphical user interface as shown in Figure 28. The STL file can be imported and the software provides 2-D and 3-D views of the design in the view menu.

Figure 28 Start-up screen

4.2.1 Import

The first step to processing any design is importing the STL file for the design. The CAD/RP program allows the STL file to be imported using a common dialogue box as shown in Figure 29.

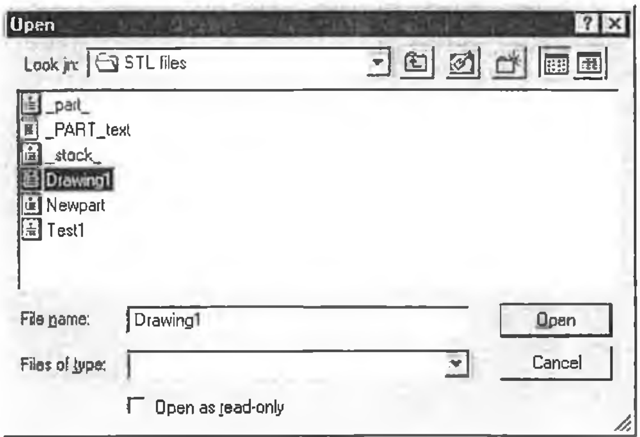


Figure 29 File open dialogue box in the CAD/RP program.

Once a file is open the software can then be used to process the file to find the maximum and minimum value for the model x, y, z coordinates this is done using the "Find_max_min" procedure.

The "Find_max_min" procedure operates by scanning the STL to find the the maximum and minimum co ordinates in the x, y, z. this is done by storing the first set of x co ordinates in the x_{max} and x_{min} variable and then comparing each subsequent x-coordinate with x_{max} and x_{min}, overwriting this value with the new coordinate if necessary. The same time is done for the y and z coordinates

4.2.2 View menu

After importing the design CAD/RP provides the capability to view the design in 2D and 3D. This gives the ability to ensure that the right design is imported before starting the slicing process. The view menu contains six commands to view the model, see Figure 30.

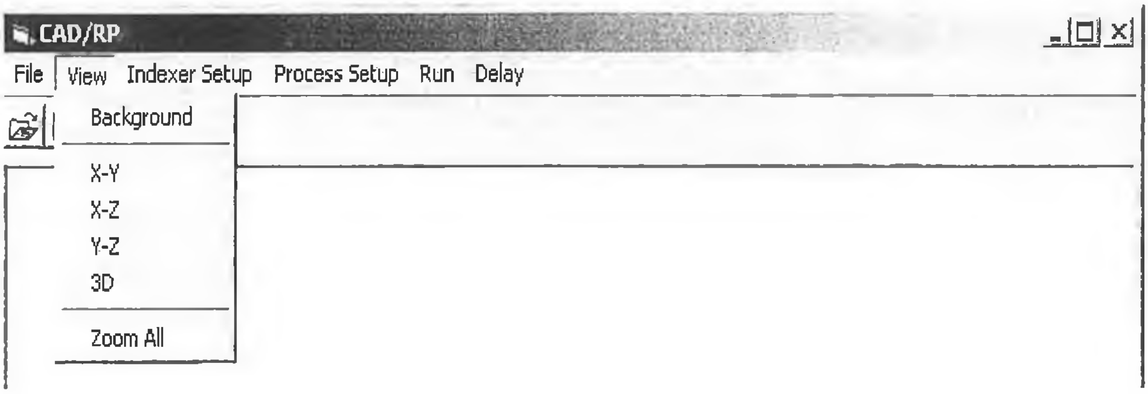


Figure 30 View menu of CAD/RP program

a. Background colour allows the background colour to be changed. When this choice is selected a colour dialogue box is called and a desired colour can be chosen.

a. The X-Y option shows the model in X-Y coordinate system. This selection calls the function "Cls" to clear the screen, opens the "triangles.txt" file for input and reads the value for the three vertex and saves only x, y as segments in a file called "Drawing.txt", see Appendix C1. After saving these segments in the "Drawing.txt" text file, The "mnuzoom" procedure called to draw the view.

b. The X-Z option shows the model in X-Z coordinate system. The same steps are taken in this procedure but only x and z values are saved as segments.

c. The Y-Z option shows the model in Y-Z coordinate system. The same steps are taken in this procedure but only y and z values are saved as segments.

d. The 3D selection is used to view the model in three dimensions. This command calls the function "Cls" to clear the screen, opens the "triangles.txt" file for input and reads the value for the three vertices. The vector for each point is calculated and rotated by 30°. The values for x& y are be read again and saved as segments in the "Drawing.txt" text file, see Appendix C2. After saving these segments in "Drawing.txt" text file, the "mnuzoom" procedure is called to draw the view.

e. The "mnuzoom" procedure scales the screen by 110% of the design size, then draws the design. Every time this procedure is called it opens the "Drawing.txt" text file, which contains the drawing. It finds the higher and lower values for x& y, then scales the screen by 110% of the maximum size. After scaling the co ordinates the procedure starts drawing the design.

4.2.3 Indexer Set-up command

The indexer Set-up is used to open the indexer set-up form which contains position mode set-up, axis set-up and motor speed set-up.

Position mode

Three positioning modes to manipulate the motor are available with X language commands. The three modes are normal, alternating, and continuous. Only normal mode can be chosen for this operation. Normal mode allows positioning of the motor in incremental moves or absolute moves, see section 3.5. An incremental move was chosen for this operation.

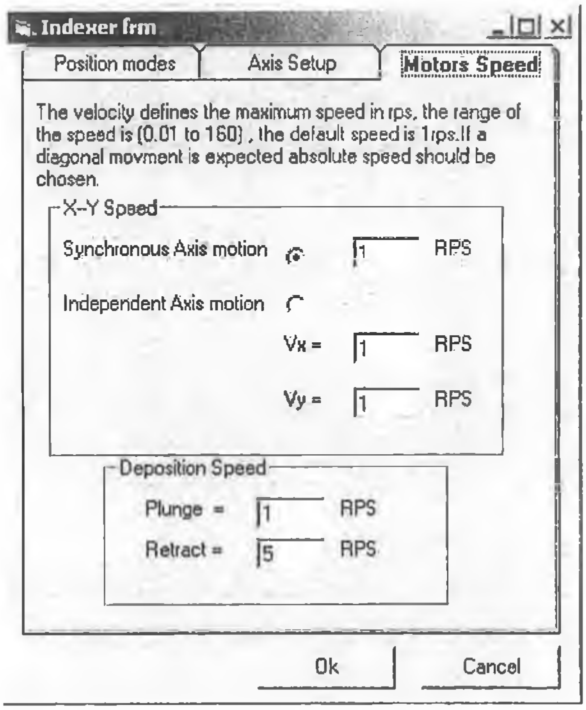


Figure 31 Position mode set-up dialogue box

Axis Set-up

Axis Set-up as an option gives a choice to select motor #1 or motor #2 for X-axis or Y-axis.movement.

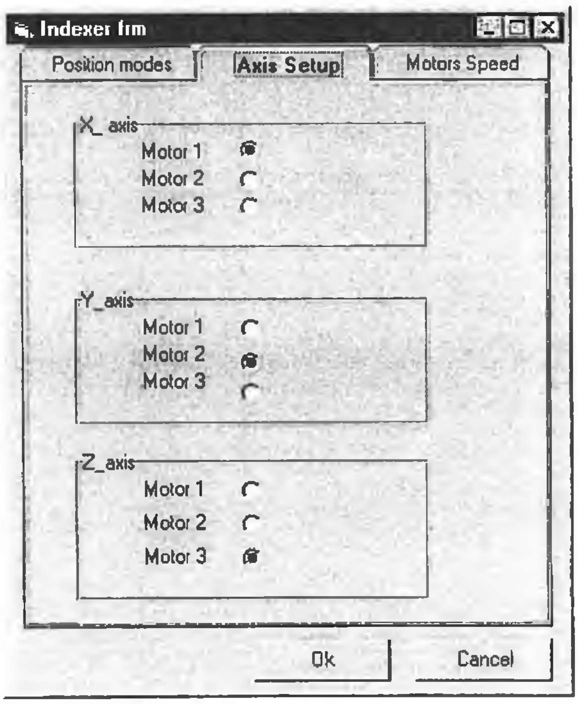


Figure 32 Axis Set-up dialogue box

Motor Speed

An absolute motion or the speed for each axis can be chosen for the indexer. If the absolute value is entered, the speed in the x and y direction will be calculated in the program. The default motor speed is 1RPS. Deposition speed can also be varied.

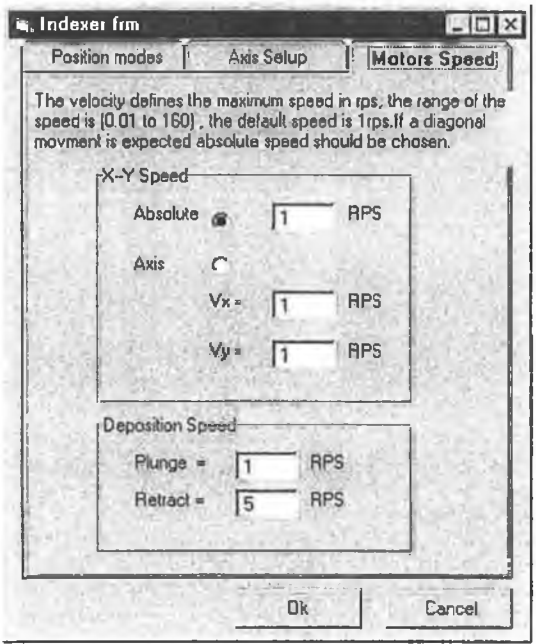


Figure 33 Motor speed set-up dialogue box

4.2.4 Process Set-up

After importing and viewing the design the second step is to process this data. Some important parameters have to be selected before starting the data processing.

The user enters the values for the layer thickness, the filling space which normally equal to the droplet width, the deposition diameter and the distance between the droplets, see Figure 34.

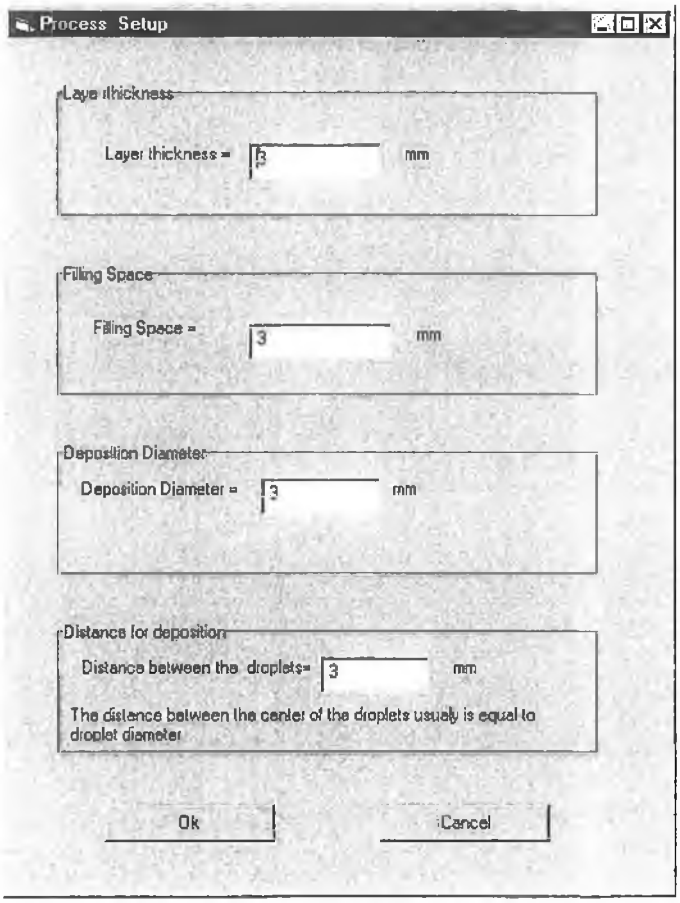


Figure 34 Process Set-up dialogue box

4.2.5 Processing Data

After the design is imported the slicing operation can be executed using the "Run" command from the Run menu or by selecting the Run button see Figure 35. The Run command executes the four algorithms: (1) The slicing algorithm. (2) The contour construction algorithm. (3) filling the pattern algorithm. (4) simulation algorithm.

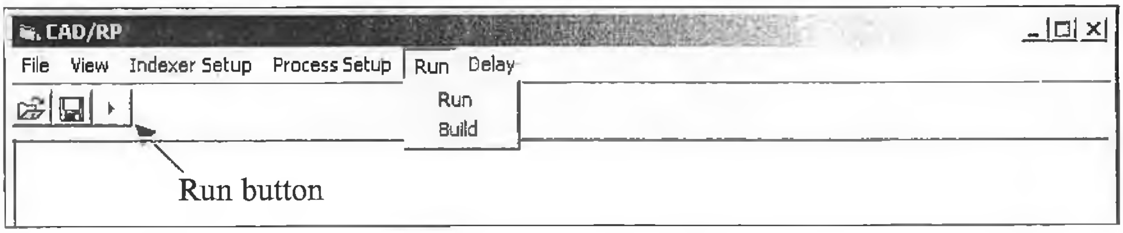


Figure 35 Run menu for CAD/RP program

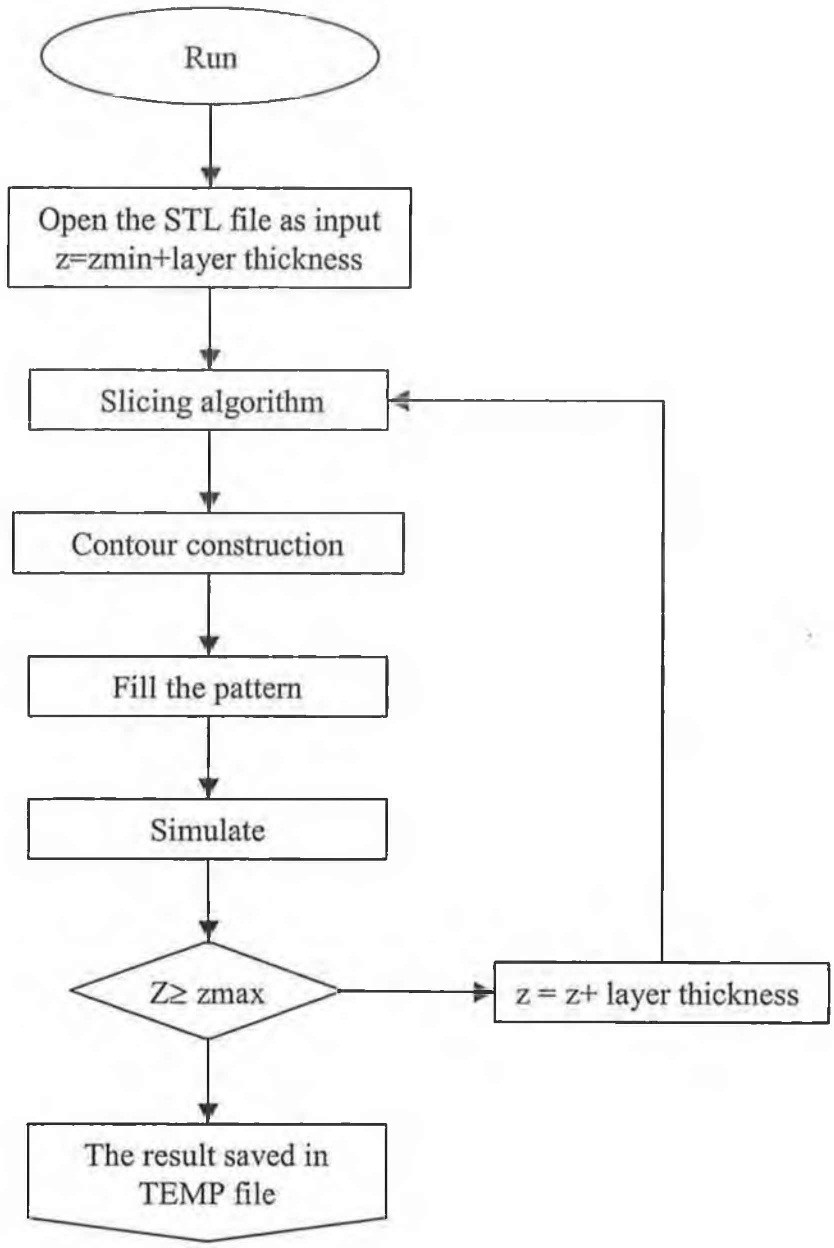


Figure 36 Run algorithm flow chart

When the run command is selected CAD/RP starts slicing the model from $Z=Z_{min}$+[layer thickness], after slicing one layer CAD/RP executes the contour construction algorithm, then executes fill pattern algorithm, then simulates the deposition of wax, and saves the deposition co ordinates for all layers in a temporary file (outfile5) for the next process, see Figure 36.

Slicing algorithm

The slicing algorithms is the main algorithm in this software, CAD/RP slices the facets in z direction, according to the four cases, see Figure 37.

Group 1. All vertices are away from the cutting plane.

Group 2. One point is in the cutting plane with the two remaining vertices are in different regions.

Group 3. One point in the cutting plane and the two remaining vertices can be above or below the cutting plane. The program ignores this group.

Group 4. Two vertices lie in the cutting plane the remaining vertex can be above or below the cutting plane. To void duplicating data the program processes the triangles whose 3rd vertex lie below the current plane and ignores those with the 3rd vertex above the plane.

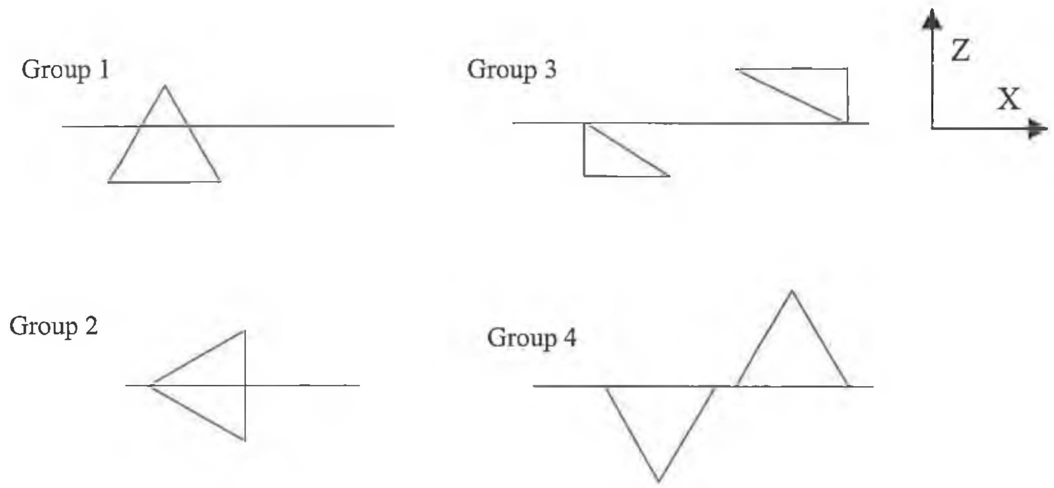


Figure 37 The possible cases examined for facet-plane slicing in the CAD/RP program.

After importing the STL file the algorithm scans the file to pick one facet at a time by searching for the "outer loop" string which means that the next three lines contain the three vertex for one triangle see Figure 2. The next three lines stored in Target1, Target2 and Target3. Vertex_x, Vertex_y and Vertex_z return the value for x, y, z for each vertex of the triangle.

For each of these triangles, the program has to find which lines of the triangle intersect with the slicing plane, by comparing the z-coordinate of each vertex with the Z-height of the current plane see Figure 38.

$z_a \leq z < z_b$

Or $z_a \leq z < z_c$

Or $z_b \leq z < z_c$

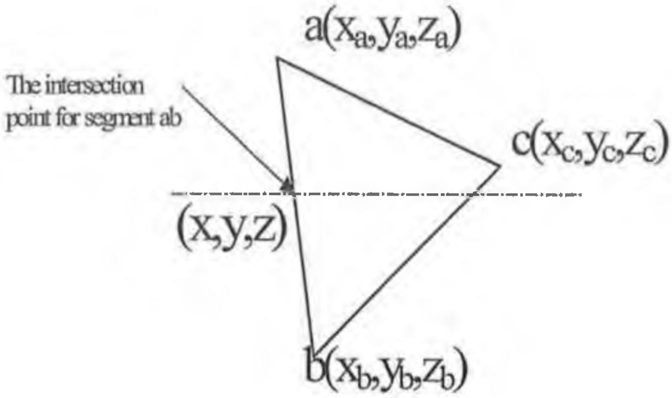


Figure 38 Three vertices of one triangle and the entersection points

For each line which intersects the plane x& y coordinates for the point of intersection is found using the general equation:

$$\frac{X - X1}{X2 - X1} = \frac{Y - Y1}{Y2 - Y1} = \frac{Z - Z1}{Z2 - Z1}$$

eg: for the segment ab.

By connecting the intersection points in each triangle, a sets of straight-lines will be formed. The slicing output is a list of lines -in a random order - forming a closed contour. See Figure 39 and Appendix C3 for this slicing code.

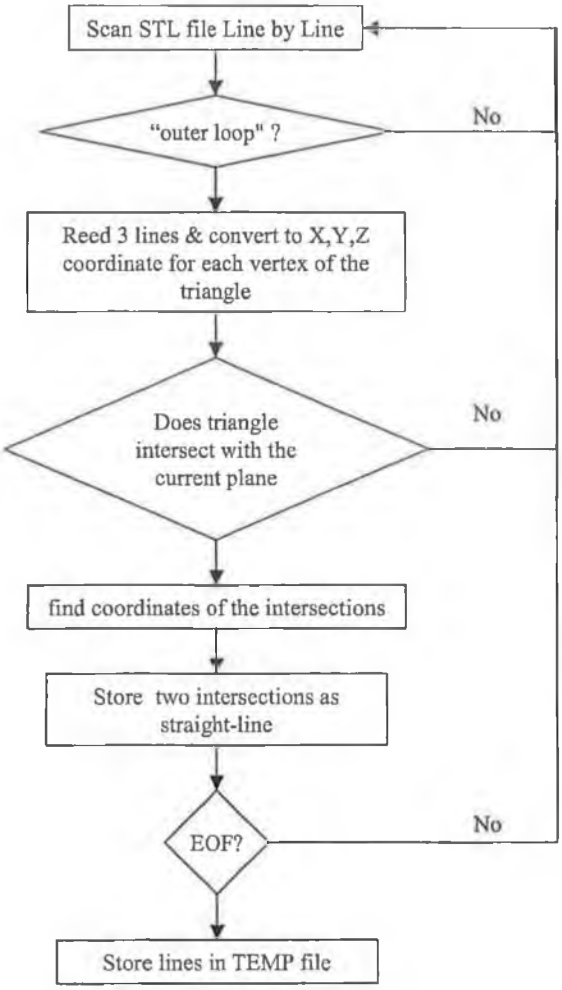
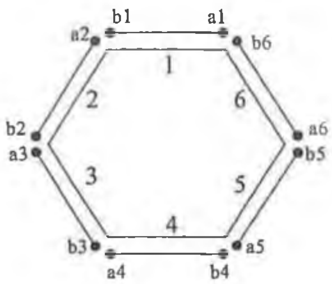


Figure 39 Slicing algorithm flow chart for CAD/RP program

Contour Construction algorithm

The set of line segments found are not in any particular order and so the list must be sorted to form a continues contour

The "Contour_ordering" algorithm is executed after the slicing operation by transferring the first segment in the list to a new list then searching for the neighbouring line. When this neighbour line is found it may need to be reordered see Figure 40. The same procedure is continued to find the rest of the contour. When the contour is closed by finding the first point in the list, the algorithm searches for any segments left in the old file. If any are found by means, the same procedure is also taken to close this contour, see Figure 41 and Appendix C4 for the related code.



Slicing list	Intermediate list	Contour list
1. (xa1,ya1),(xb1,yb1)	1.(xa1,ya1),(xb1,yb1)	1. (xa1,ya1),(xb1,yb1)
3. (xa3,ya3),(xb3,yb3)	2. (xb2,yb2),(xa2,ya2)	2. (xa2,ya2),(xb2,yb2)
5. (xa5,ya5),(xb5,yb5)	3. (xa3,ya3),(xb3,yb3)	3. (xa3,ya3),(xb3,yb3)
2. (xb2,yb2),(xa2,ya2)	4. (xb4,yb4),(xa4,ya4)	4. (xa4,ya4),(xb4,yb4)
6. (xb6,yb6),(xa6,ya6)	5. (xa5,ya5),(xb5,yb5)	5. (xa5,ya5),(xb5,yb5)
4. (xb4,yb4),(xa4,ya4)	6. (xb6,yb6),(xa6,ya6)	6. (xa6,ya6),(xb6,yb6)

Figure 40 Contour sorting

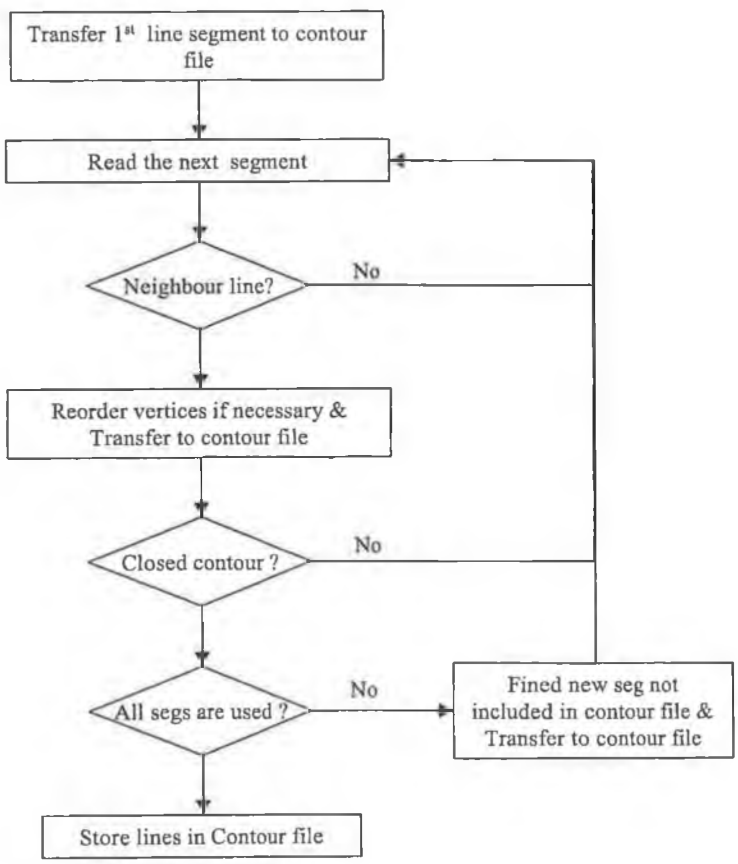


Figure 41 Contour construction algorithm flow chart for CAD/RP program.

Filling the pattern algorithm

After defining the cross-section of the slices, the interior of the slice has to be filled with the material. There are many patterns used to fill the contour. Raster contour filling, one of the most commonly used styles is used in this algorithm.

When a straight line intersected with the contour in the x-y plane an even number of intersections, will occur see Figure 42. By counting the number of intersections, and sorting the intersection points from minimum to maximum in the X direction, the segment between the first and the second intersection is inside the contour and will be saved in "filled_pattern" file. The segment between the second and the third intersection is outside the contour and it will be ignored etc. When the lines are tangential to the contour the point of contact must be counted twice as an intersection. To sort a large number of intersections the author developed an algorithm to sort up to 100 intersections see Appendix C5 [57].

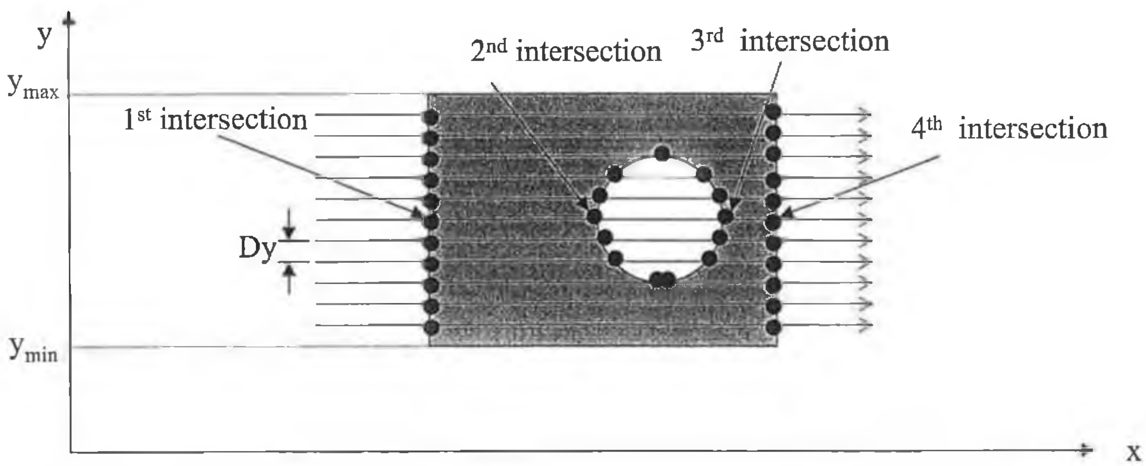


Figure 42 Contour filling point selection illustration.

After finding the intersection in the level y, a filling space Dy is added to y to find the intersection for the next movement, see section 4.2.4, and Figure 43.

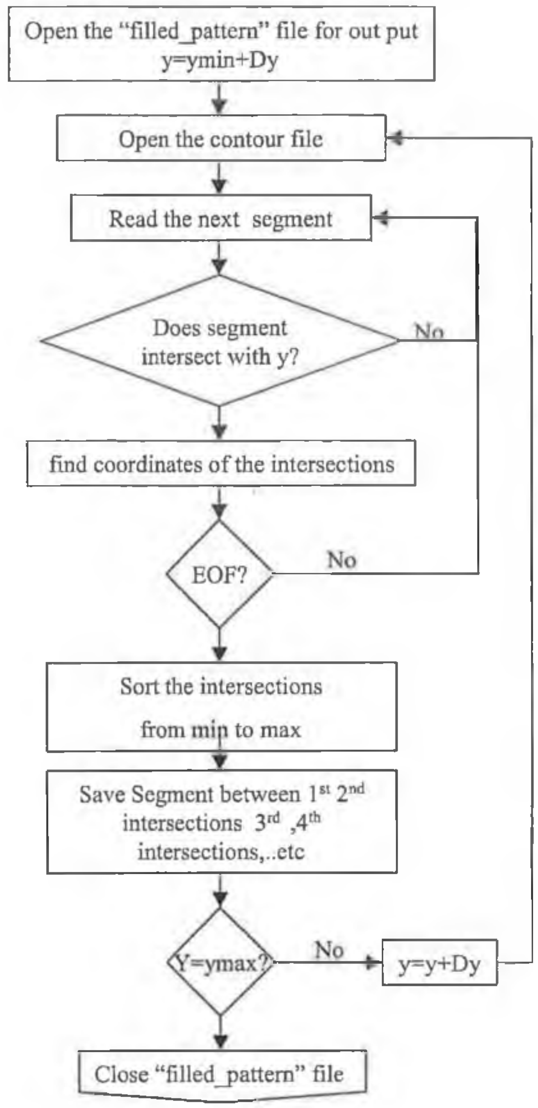


Figure 43 Flow chart for the contour-filling algorithm

Wax droplet simulate algorithm

To simulate the deposition of wax the algorithm starts by opening the "contour" file, which contains the continues contour, and reading the first segment [(x1, y1), (x2,y2)]. If its length L is smaller than the wax diameter D read the next segment. If L equal to D move to (x2, y2), if (L) is greater then D divide the interpolation into steps equal to D. When "contour" file finish, the algorithm opens the "filled pattern" file, which contains the filling pattern segment, the and the same steps will be taken. To have consistency in filling the pattern when interpolation reaches one side of the part the next interpolation will be in the opposite direction. All these positions obtained will be saved in a file called "deposition_positions" file see Appendix C6 for the code.

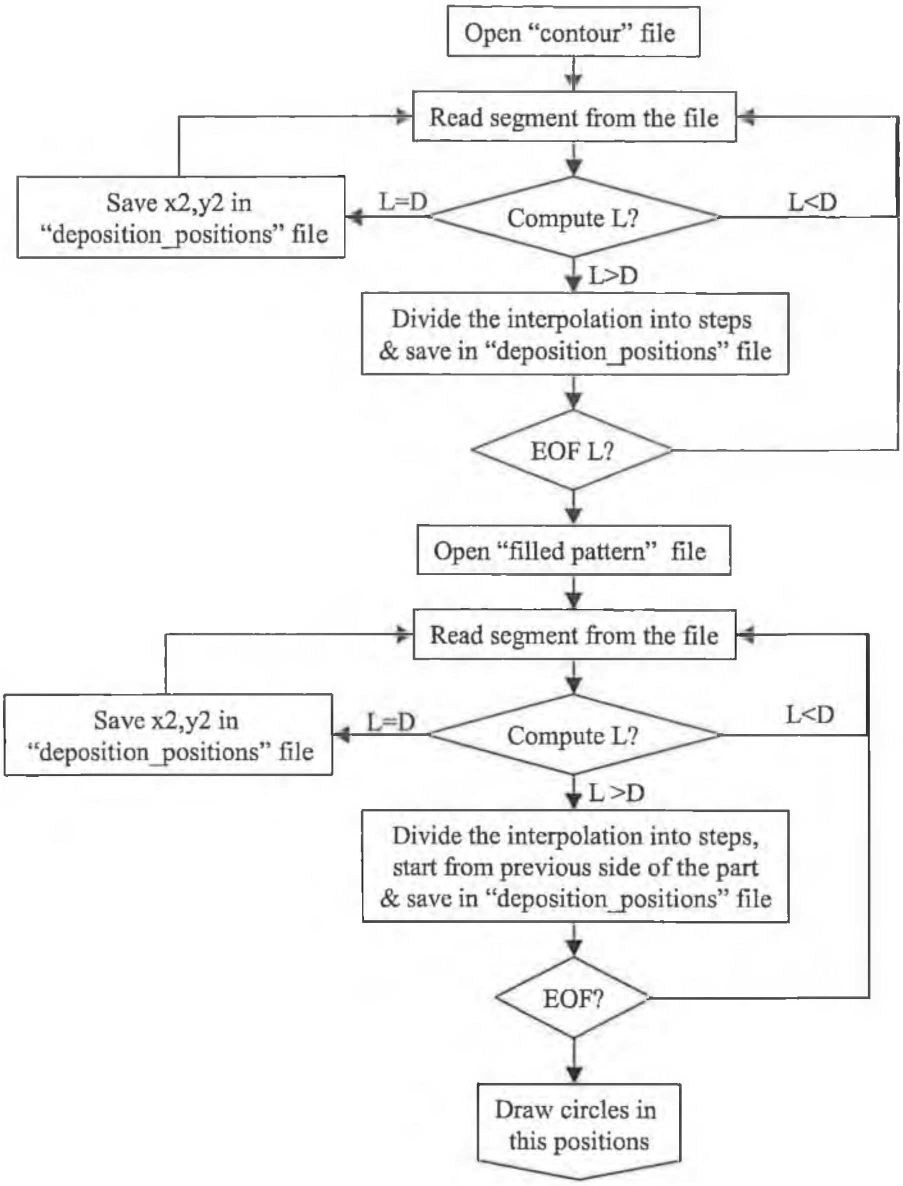


Figure 44 Flow chart for simulation algorithm

Build the instruction command file

After all the deposition positions are obtained and simulated, CAD/RP can build the PC23 commands. When the build command is selected from the Run menu -see Figure 35- the build algorithm will be executed. The instruction command file consists of three-command strings: (i) move commands, (ii) deposition command and (iii) retract command.

Move commands

Move commands are build to control the precision manipulator in x-y plane. To construct the move commands the algorithm opens the "deposition_positions" file as an input file, calculates the movement in the x, y directions and the speed for each motor. The Move command consist of two parts, the first part carries the movement in the x direction to motor1 or motor 2 depending on the previous set-up, the second part carries the movement in y direction to the other motor. If an Synchronous Axis motion is given in the speed the set-up form, the motor speed has to be calculated in x& y direction to give a correct diagonal movement. There are three possible cases to move the deposition head:

1. Movement in x direction only: in this case the speed in x direction is equal to the absolute speed, which is set in Motor speed form. The motor steps calculated using the next equation.

   $$Dx = (X2 - X1) * 5000 * \tfrac{2}{3}$$ *Equation 1*

   where 5000 is number of steps in 1.5 mm.

   The command string is constructed by adding the number of motor steps and the speed in the "first_part" string.

2. Movement in y direction only: in this case the speed in y direction is equal to the absolute speed and the motor steps calculated using the next equation.

   $$Dy = (Y2 - Y1) * 5000 * \tfrac{2}{3}$$ Equation 2

   The command string is constructed by adding the number of motor steps and the speed in the "second_part" string.

3. Movement in x and y direction: in this case the total speed v_t is given and the speed in the x& y direction is calculated using the next equation and the motor steps calculated as above.

$$v_x = v_t \Big/ \sqrt{1 + \left(\frac{D_x}{D_y}\right)^2}$$ *Equation 3*

$$v_y = v_x \times \frac{D_x}{D_y}$$ *Equation 4*

Command string constructed by adding the number of motor steps and the speed into the “first_part” and the “second_part” strings.

Deposition command and retract command:

The deposition command and retract command are a fixed string and will be sent after each movement to motor 3. The deposition command is constructed to deposit the wax and retract command to hold the wax.

The leadscrew for the power transfer apparatus for motor 3 has a larger pitch of 2mm, this gives a bigger resolution, the shaft rotation is divided into 5000 steps, and therefore the linear movement for one step is equal to 0.0004mm. The distance for plunge movement is 12mm (30000 steps); the distance for retraction movement is 11.991mm (29979 steps), this 21 steps differential is for the loss of wax volume it was found also that a gradual plunge movement(V1) and slower reaction movement (V2) gave the better results [56] .

After constructing the moving command for motor one and two, the result command written in one string, and the deposition command is written each time. The command strings were saved in “motor_strings.txt" file. See Appendix C7 for the code.

Delay

Delay is an option to slow the simulation operation for better understanding of the tool path and the wax deposition. The time between each simulation step is controlled by the delay parameter. Long delays means slower simulation.

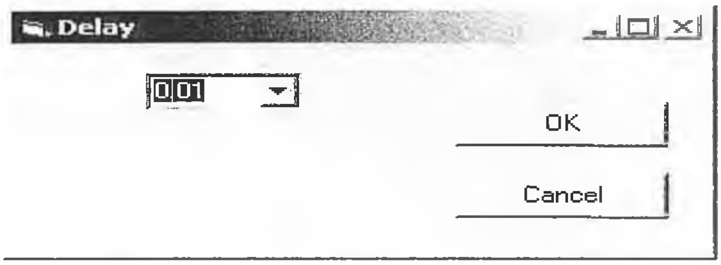


Figure 45 Delay form for CAD/RP

Save algorithm

When save command is selected a Save Common Dialog is called -see Figure 46- to save the command strings file in a text file. CAD/RP reads the typed name and open “motor_strings.txt" for input and the new file name as out put the algorithm reads from input file and write in the out put file.

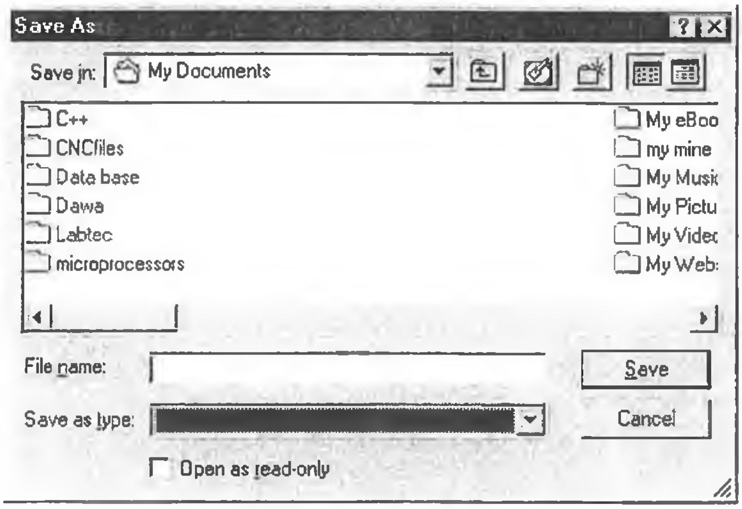


Figure 46 Save common dialogue box

4.3 Introduction of Using CAD/CAM for RP

Many existing CAD/CAM software packages are used to generate the tool path for milling operations. There is a big similarity between the milling operation and deposition operation. The idea was to use existing CAD/CAM software to generate the tool path. AlphaCAM™ generates the tool path for CNC machining in G code format. To use this code for the PC23, software was developed called CNC/RP to process the G code by performing the next steps:

1. Scanning the CNC code,
2. Manipulating the tool path,
3. Simulate the deposition of wax,
4. Filtering the additional deposition in some areas,
5. Translates the CNC code to X-language codes, which are the PC23 indexer instructions and
6. Saves these instructions in the text file, or export the instructions to build the part.

4.3.1 Generate CNC Code for rapid prototyping

AlphaCAM is fully featured CAD/CAM software used to generate the tool paths for CNC machines it is developed by LICOM, which is part of the Planit group - a global company specialising in the development and distribution of software to the woodworking and engineering industries, situated in England.

To generate a tool path suitable for use in RP the following must be considered:

a. The part must be machined not the extra material. For example to produce the round rectangular in Figure 47 by milling. The grey area must be machined but to build this in rapid prototyping the tool path for the white area has to be created.

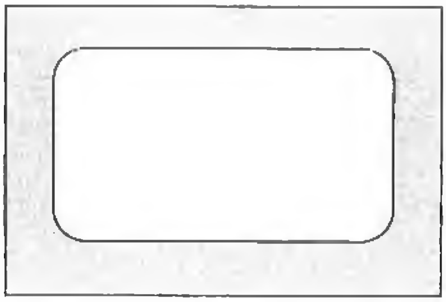


Figure 47 Generate CNC code for RP from AlphaCAM

5. Wax droplet RP system has no need to move in Z direction; therefore the z value can be ignored for the operation.

6. Parameters in the AlphaCAM software must be set according to the specification needed in the building operation, so the tool diameter can be set as a deposition wax diameter, and the milling depth as droplet height. A very small tool diameter can be set in AlphaCAM to generate a very precise tool path.

7. All non-machining movements should be rapid, to enable the software to distinguish between the build movement and the movement without building.

8. All the geometry in the same level has to be machined before the next level.

4.3.2 Example of Using Alpha CAM to generate CNC code for RP

This is an example of using Alpha cam to generate machining code for a rectangular pocket with a 21 mm length and 18mm in width to the depth of 6 mm, these are the Steps to generate a tool path in AlphaCAM

Step 1 :Open the software:

Open the AlphaCAM folder then click on the "Advanced 3D Milling"

Step 2: Define the material:

- Select geometry, then Line, then draw a square

- Click on the "set material size" icon, pick the outline of the square that you have just drawn, enter (0) for the Z value at the top of the material, enter a negative value less than –6 for the Z value at the bottom of the material, so that the depth of material is greater than the depth of the pocket.

Step 3:Define the shape to be machined

- Design the part: Size: 21*18 mm.

Step 4: Tool selection

- Click on the "Select" icon
- Scroll down the list and pick "Flat 3mm 2F EC HSS"
- Press enter to accept the tool.

Step 5. Tool Directions

- Select "CCW" for directions
- Select "Inside" for the Side.

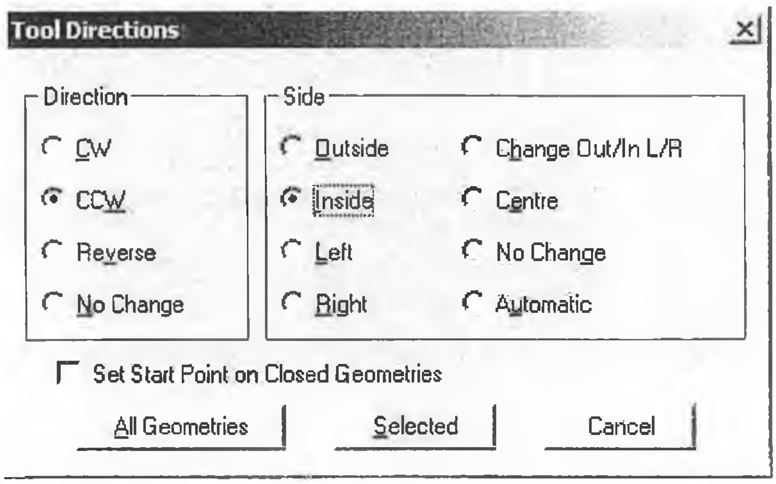


Figure 48 Tool Directions form in AlphaCAM software

Step 6. Pocketing: Click on the "Pocketing" icon

- Select "Vertical" for Sides

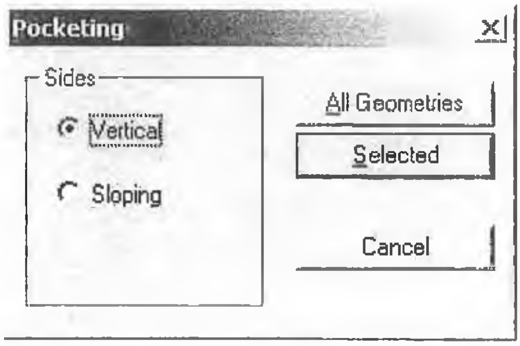


Figure 49 Pocketing form1 in AlphaCAM software

- Click on "selected" to select the geometry.
- Click on Ok to select the options presented.

Step 7: Pocketing

- Enter "1" for Operation No
- Select "Linear" for Type
- Select "Full" for Final Pass Around Islands

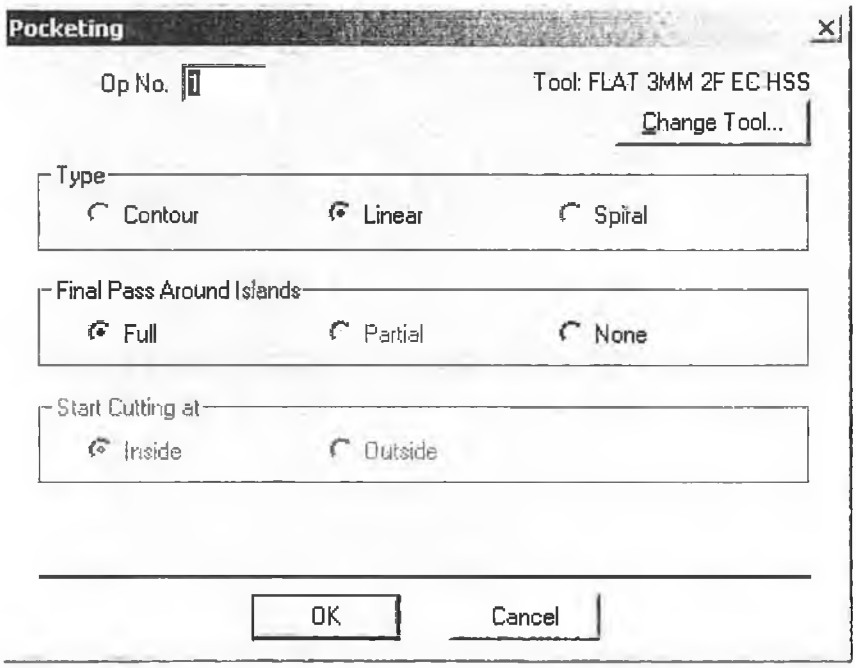


Figure 50 Pocketing form 2 in AlphaCAM software

Step 8:Linear Pocket Sides Vertical

- Enter 0 for “safe rapid level”
- Enter 0 for “Rapid down to”
- Enter 0 for “Material Top”
- Enter -6 mm for “Final depth”
- Enter 3 for number of cuts
- Click on Ok
- Select “: Linear” for NC Code for Multiple Cuts
- Select “by Level” for Cutting Order
- Select “Equal” for Depths of cut

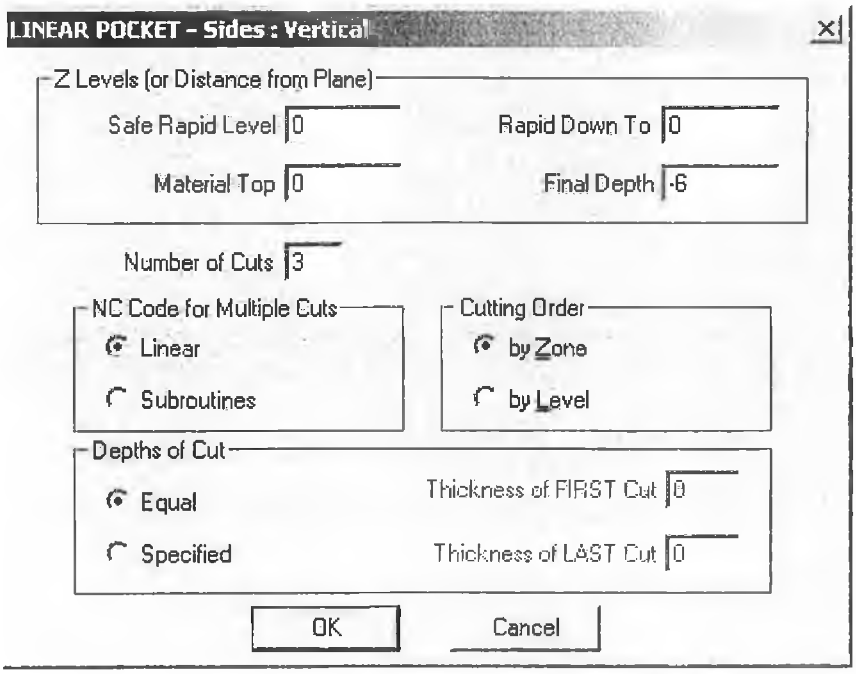


Figure 51 Linear Pocket Sides Vertical form in AlphaCAM software

Step9: Linear Pocket – Tool: Flat 3mm 2F EC HSS

- Enter “1” for Tool Number
- Enter “1” for Offset Number
- Enter “3” for Diameter

➢ Enter "4000" for Spindle Speed

➢ Enter "10" for Down Feed

➢ Enter "20" for Cut Feed

➢ Enter "0" for Stock to be Left

➢ Enter "3" for Width of Cut = 3 mm

➢ Select "None" for Coolant

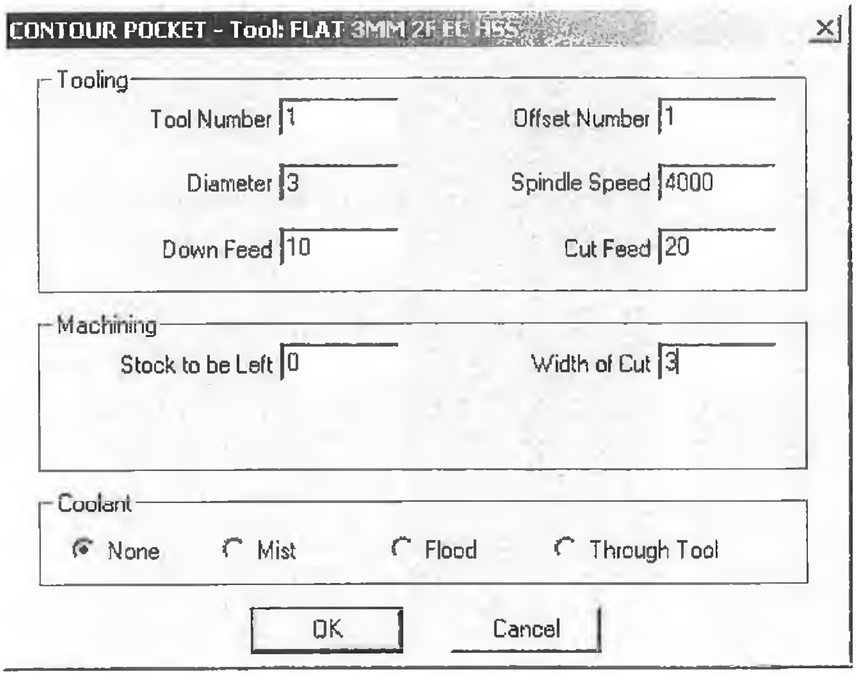


Figure 52 Linear Pocket – Tool: Flat 3mm 2F EC HSS form in AlphaCAM software

➢ Select Ok to select the options presented.

Step 10: Tool Path Resulted

➢ Click on the green geometry with the mouse.

➢ Click on finish.

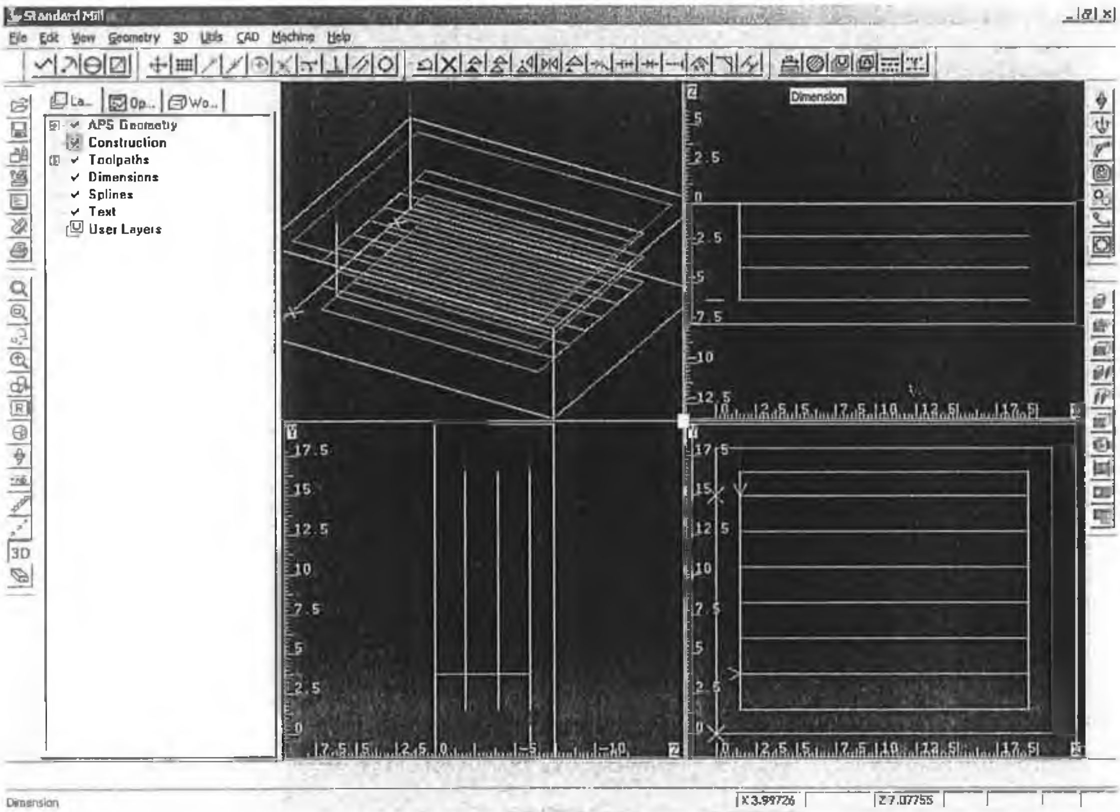


Figure 53 Tool Path Result for the rectangular

Step 11: Save NC code for this process

- Select; File -> Output NC.
- Give the file a name and save it to your home directory.

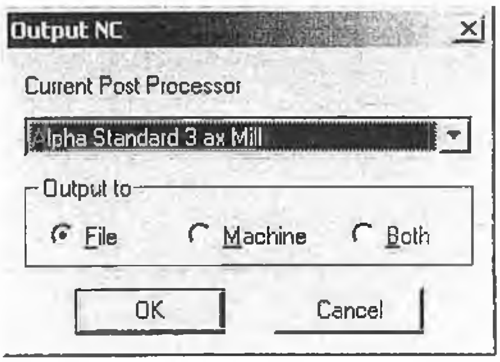


Figure 54 Output NC.form

Figure 19 shows the out put CNC code, the code consists of the head which contains comments from AlphaCAM, the main program which contains the main G code for the milling operation and the sub-program which contains the sub-routine which is part of the program that is repeated a few times.

4.4 Development of CNC/RP software

CNC/RP user-friendly software is designed to generate control commands for the PC23, to build a prototype from CNC code, which was generated in AlphaCAM. Figure 55 illustrates the entire available commands and algorithms in the CNC/RP software.

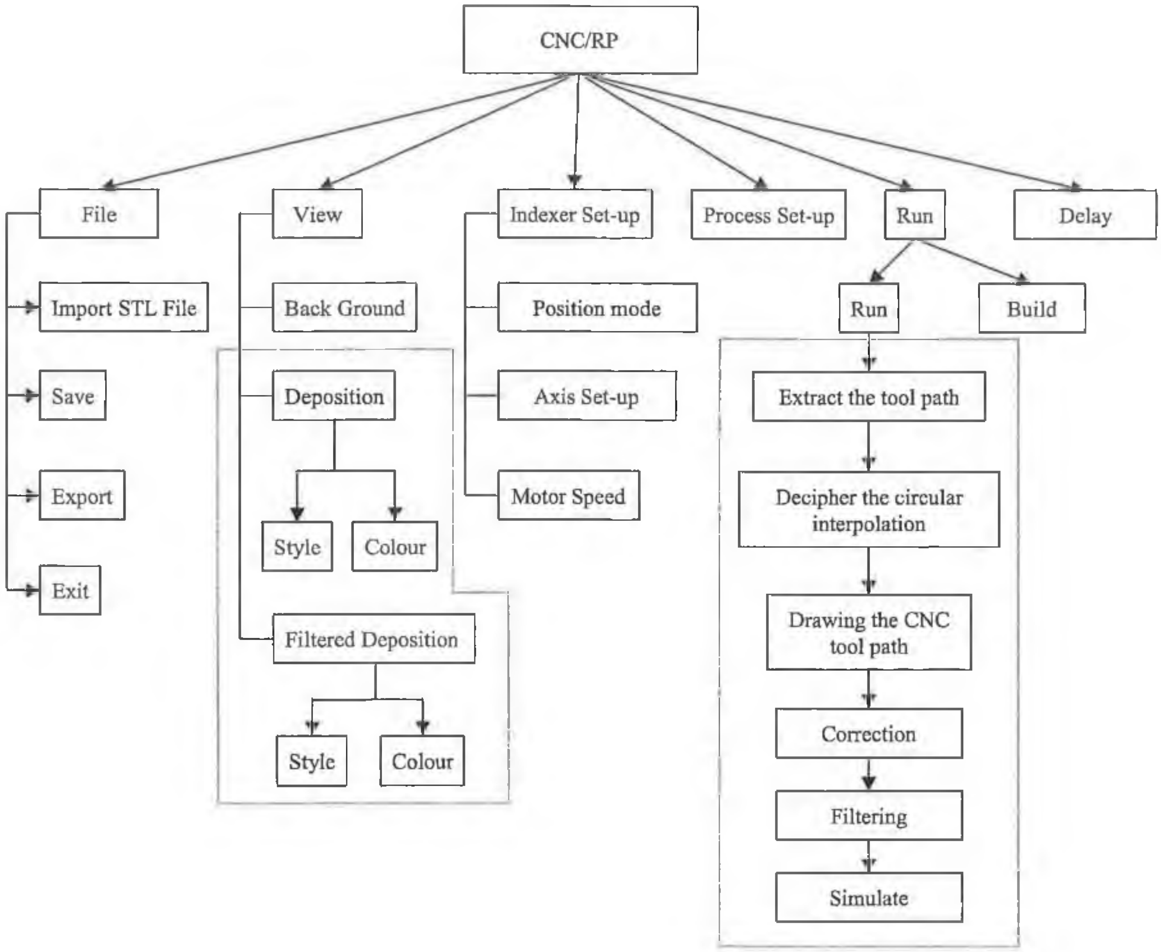


Figure 55 Structure of the CNC/RP program

The highlighted sections in Figure 55 are the additional sections coded for the CNC/RP program, which were not available in the CAD/RP program.

CNC/RP provides a single document graphical user interface as shown in Figure 56. It imports the CNC file and provides 2D graphical interface to view the tool path, which was generated in AlphaCAM.

Figure 56 Start-up screen

4.4.1 Import

The first step to processing any design is importing the CNC file code for the design, CNC/RP imports the CNC file using import command from File menu see Figure 57 import command calls a common dialogue box to read the imported file name.

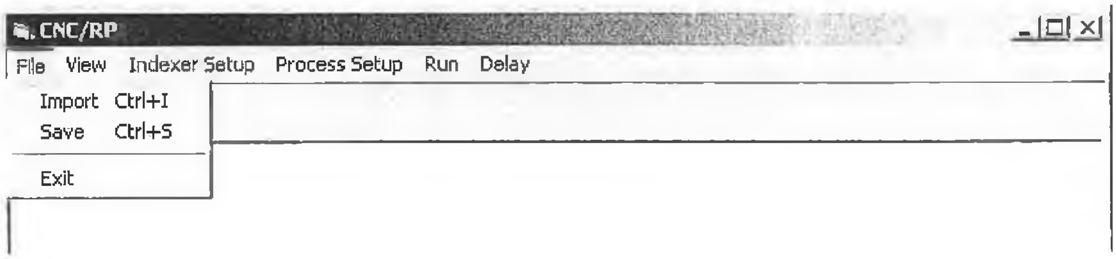


Figure 57 Import command.

4.4.2 View menu

CAD/RP provides capability to view the tool path and the simulation process in 2D view, this gives the ability to insure that the right file is imported and the simulation is acceptable before building the instruction command file. View menu contains sub menus to view the deposition and filtered wax in different colours, see Figure 58.

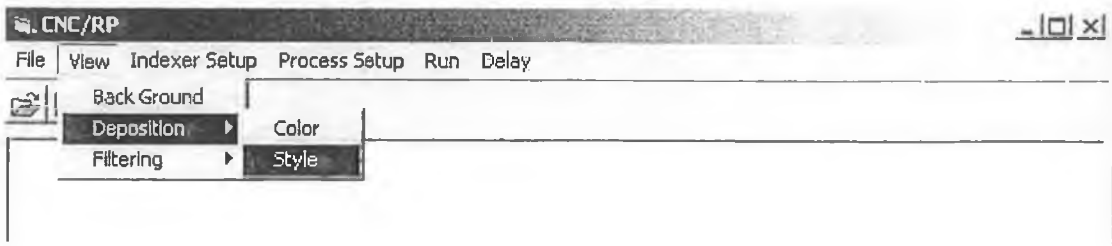


Figure 58 View menu

a. Background colour to give a better view, when this command pressed a colour dialogue box is called and a new colour can be chosen.

b. Colour and style deposition of wax.

c. Colour and style filtered deposition.

4.4.3 Indexer Set-up

Indexer set-up command downloads the indexer set-up form which contains position mode set-up, axis set-up and motor speed set-up. This form was used in CAD/RP and explained in section 4.2.3.

4.4.4 Process Set-up

After importing the second step is to process this data. Some important parameters have to be selected before starting the processing the data.

The program reads the filling space, the deposition diameter, and the distance between droplets see Figure 59. The CNC/RP processes the data automatically after importing the CNC code, for that reason these parameters have to be set before importing the code.

a. Cord length: this value is needed to calculate the values of x & y on the arc, if the interpolation is circular, a smoother arc will be achieved with a smaller value.

b. Droplet diameter: the droplet diameter has to be specified to enable CNC/RP to simulate the deposition.

c. Distance between the droplet: if this distance is not equal to the droplet diameter it has to be specified to calculate the motor steps for each movement, to generate the instruction commands for the PC23

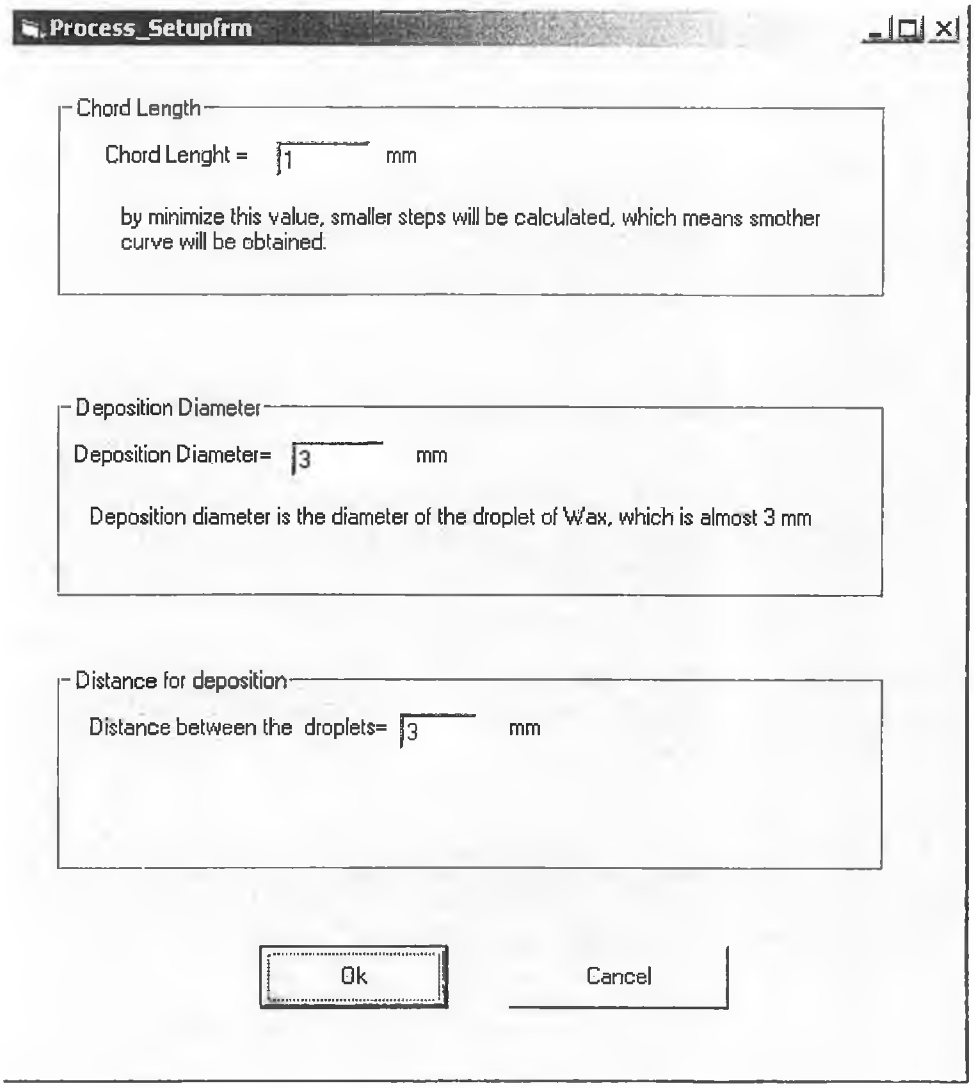


Figure 59 Indexer set-up form in CNC/RP program.

4.4.5 Processing Data

After the CNC file is imported, Run command can be executed by selecting the Run button. The Run command executes four algorithms: (i) Extract, (ii) Draw, (iii) Simulate and (iv) Correction. CNC/RP can execute these operations step by step from Run menu by selecting each command button see Figure 60.

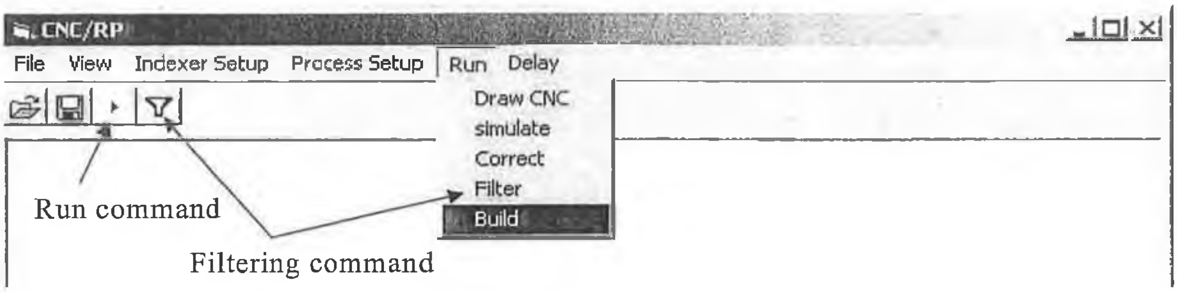


Figure 60 Rum menu

When CNC/RP is executed the program opens the selected CNC file as a sequential input file, reads the text line-by-line, extracts all needed information such as G codes, the displacements in x, y, z and R, manipulates the tool path, simulates the deposition of wax, filtering the additional deposition in some areas, and then translates the CNC code to X-language codes, which are the PC23 indexer instructions to drive the motors.

The program flow is divided into seven steps:

1. Extract the tool path.

2. Drawing the CNC tool path.

3. Simulate.

4. Correction.

5. Filtering.

6. Build the instruction command file for PC23

7.Save

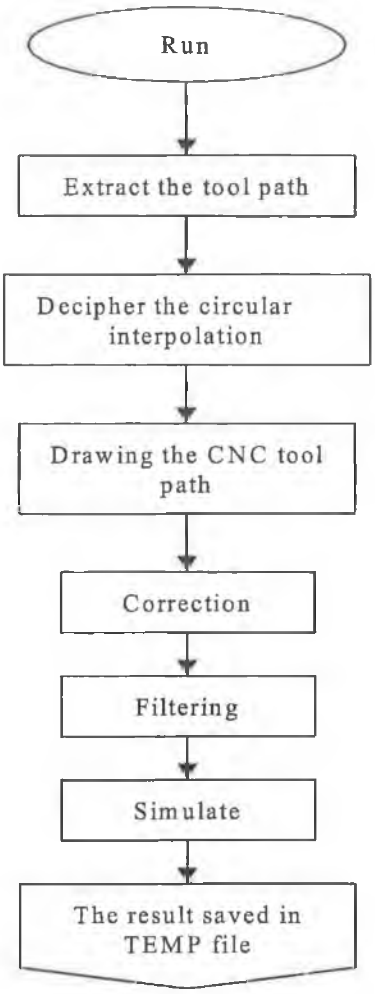


Figure 61 CNC/RP run algorithm flow chart

a. Extract the tool path

In this step the program opens the CNC text file as a sequential input file, reads the text line-by-line, searches for G0, G1, G2, G3, X, Y, Z, I, J, R and M98. G0, G1, G2, G3 are modal commands, which means if any of them appear it will remain in effect until another modal command is found. The program keeps the previous command in effect until the next G is found. The program uses [InStr(target str, "sub str")] function to search for "sub str" string in "target str", this function returns the position of sub string in target string, if the value is greater then zero this means the sub string is found

The program uses the previous function to Search for "X" string then uses the "Mid$(StringExpression, Start Position, NumberOfCharacters)" function which returns specified section from the string[58]; this section starting from the position of

"X" in target string plus one. The same procedure is followed to find the values for Y, Z, I, J and R, see Appendix D1 for the code.

The program searches for "M98". "M98" means the CNC code contains a sub program, to track the same tool path CNC/RP has to go to the sub program as well, when the sub program finish CNC/RP has to go back to the same position in the main program. This operation performed by splitting the CNC sub program and the main program into two different text files. To decrease the error AlphaCAM can be set to generate the code without any sub program, CNC/RP is intended to read only one sub program.

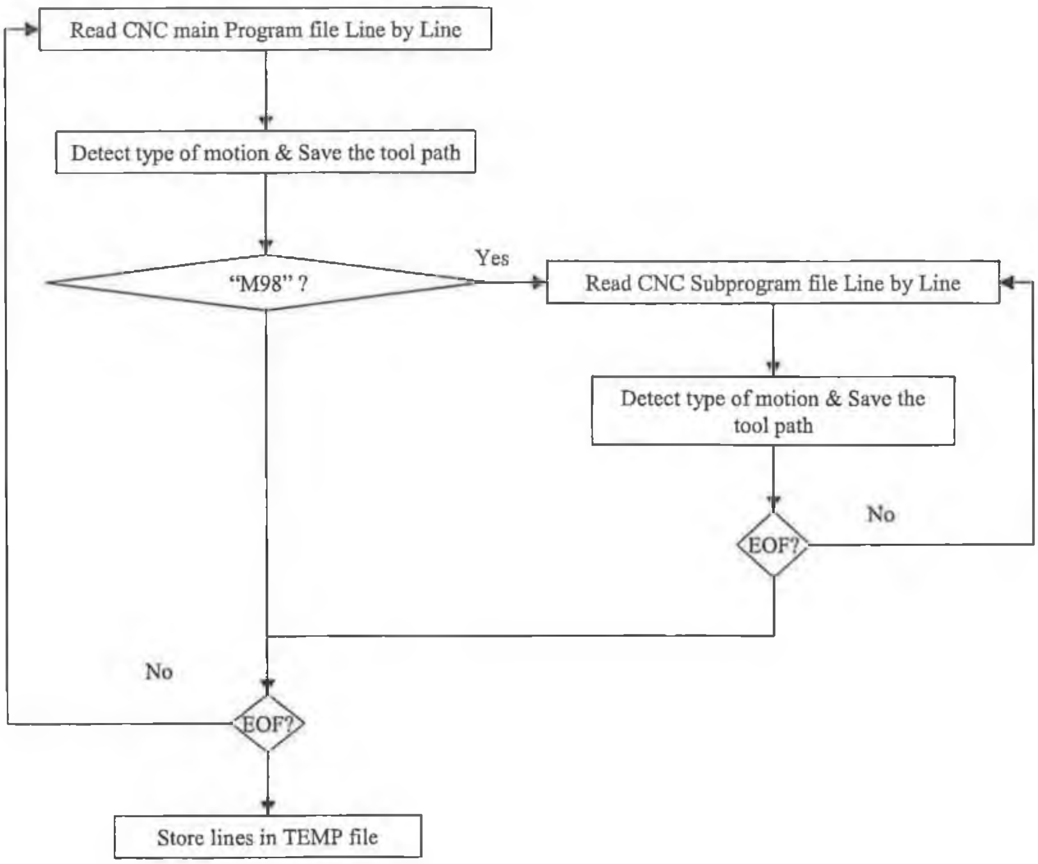


Figure 62 Extract algorithm flow chart

CNC AlphaCAM text file can contain some comments, which may cause errors in identifying the tool path, so another procedure has to be taken to check for only the numerical values after the command strings. IsNumeric(a) function returns true if the whole string is numerical, this function is used to check only the digit after X,Y, Z, I, J and R. If IsNumeric(a) returns true, Val(str) function continues to read the string and returns the numerical values only. The program saves the numerical values only in a new text file using Write command. Alph-Cam can be also set to generate the code without any comments.

b. Decipher the circular interpolation

The saved data in the last step is the useful data to control the motion of the PC23, except the circular interpolation, which is represented using the radius method, radius method specifies the motion with the radius R, the start point P1 (x_1,y_1) and the end point P2 (x_2,y_2). PC23 cannot generate circular motion using the radius and the end position therefore the arc has to be described with x-y steps. To do so the coordinate of the midpoint Pm of the line L joining the two points must be determined see Figure 63.

$$x_m = \frac{x_1 + x_2}{2} \quad , \; y_m = \frac{y_1 + y_2}{2}$$ *Equation 5*

Let the half differences in coordinates be:

$$x_{12} = \frac{x_1 - x_2}{2} \quad , \; y_{12} = \frac{y_1 - y_2}{2}$$ *Equation 6*

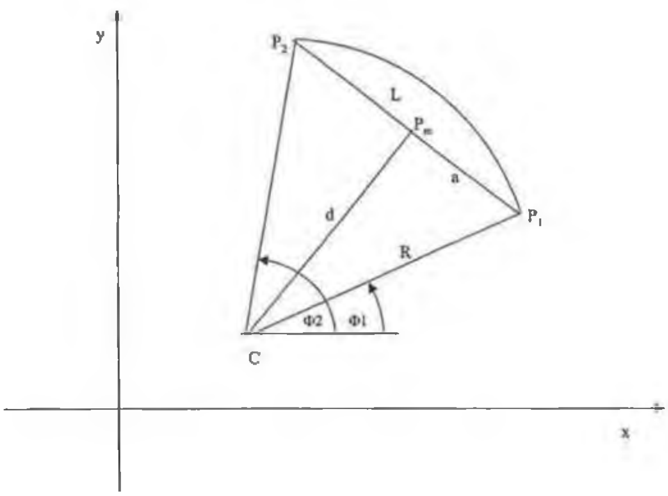


Figure 63 Define Circular interpolation for PC23

Compute the slope of the line L

$$u = \frac{y_2 - y_1}{x_2 - x_1} \quad \text{Or} \quad u = \frac{y_{12}}{x_{12}}$$ Equation 7

The slope of the perpendicular through the centre u_c is equal to

$$u_c = \frac{y_m - y_c}{x_m - x_c} \qquad \textit{Equation 8}$$

$$u = \frac{-1}{u_c} \quad \text{Then} \qquad \textit{Equation 9}$$

$$u = -\frac{x_m - x_c}{y_m - y_c} \qquad \textit{Equation 10}$$

Now compute the distance between the centre and the mid point using Pythagoras theory.

$$d = \sqrt{(xm - xc)^2 + (ym - yc)^2} \qquad \textit{Equation 11}$$

By solving 10 and 11

$$xc = xm \pm \frac{d}{\sqrt{1+u^2}} \qquad \textit{Equation 12}$$

$$yc = ym \pm \frac{d}{\sqrt{1+u^2}} \qquad \textit{Equation 13}$$

Using the same theory the distance a & d will be calculated.

$$a = \sqrt{\left(\frac{x_1 - x_2}{2}\right)^2 + \left(\frac{y_1 - y_2}{2}\right)^2} \quad Or \quad a^2 = x_{12}^2 + y_{12}^2 \qquad \textit{Equation 14}$$

$$d^2 = R^2 - a^2 \qquad \textit{Equation 15}$$

From Equation 14 & 15

$$d^2 = R^2 - (x_{12}^2 + y_{12}^2) \qquad \textit{Equation 16}$$

If we substitute d from Equation 16 and u from Equation in Equation 12 & Equation 13 we obtain.

$$x_c = x_m \pm y_{12}\sqrt{\frac{R^2}{x_{12}^2 + y_{12}^2} - 1} \qquad \textit{Equation 17}$$

$$y_c = y_m \pm x_{12}\sqrt{\frac{R^2}{x_{12}^2 + y_{12}^2} - 1}$$ *Equation 18*

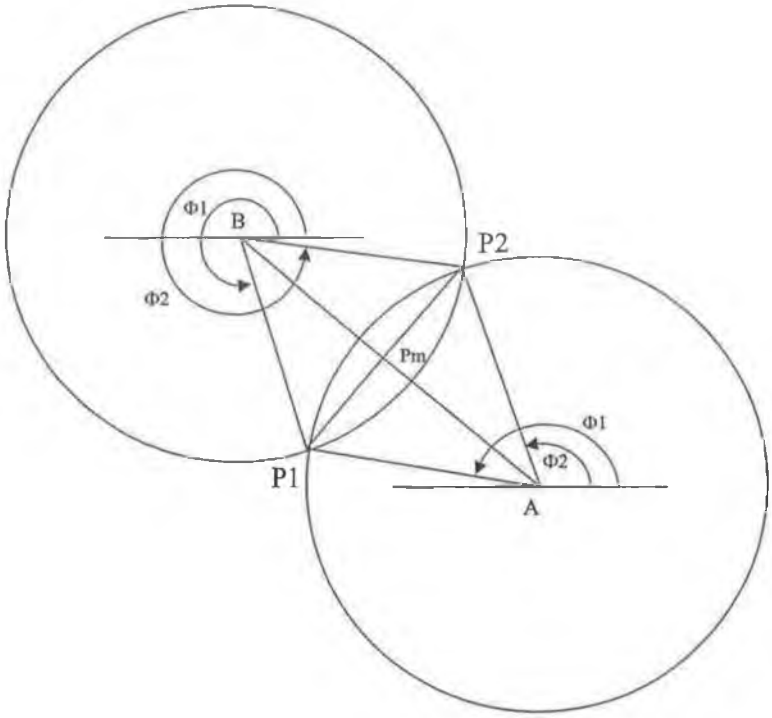


Figure 64 Circular interpolation

These two equations will give two centres. For each centre two possible arcs are possible. In general, the problem of joining two points with an arc of a given radius has four solutions: Clockwise interpolation with long or short arc, counter clockwise interpolation with short or long arc [59].

To perceive the long and the short arcs, the angle Φ_1 formed by the line joining the start point and the centre with the x-axis, and the angle Φ_2 formed by the line joining the end point and the centre with the x-axis, see Figure 63, will be calculated for each centre, using the atan2 function which returns an angel between 0 and 2π. Visual Basic does not compile atan2 function, the author proposed a similar function to return a similar value see Appendix D2.

$$x_{1c} = x_1 - xc \qquad y_{1c} = y_1 - y_c$$
$$x_{2c} = x_2 - xc \qquad y_{2c} = y_2 - y_c$$ *Equation 19*

See Figure 63

$\Phi_1 =$ atan2(y_{1c},x_{1c})

$\Phi_2 =$ atan2(y_{2c} ,x_{2c})

CNC code specifies the type of interpolation by issuing G2 for clockwise or G3 for counter clockwise, if the interpolation is going through the longer arc a sign "-" is issued before the R command. After calculating the different $|\Delta\Phi| = \Phi_2 - \Phi_1$ CNC/RP can decide which centre is the right for the interpolation.

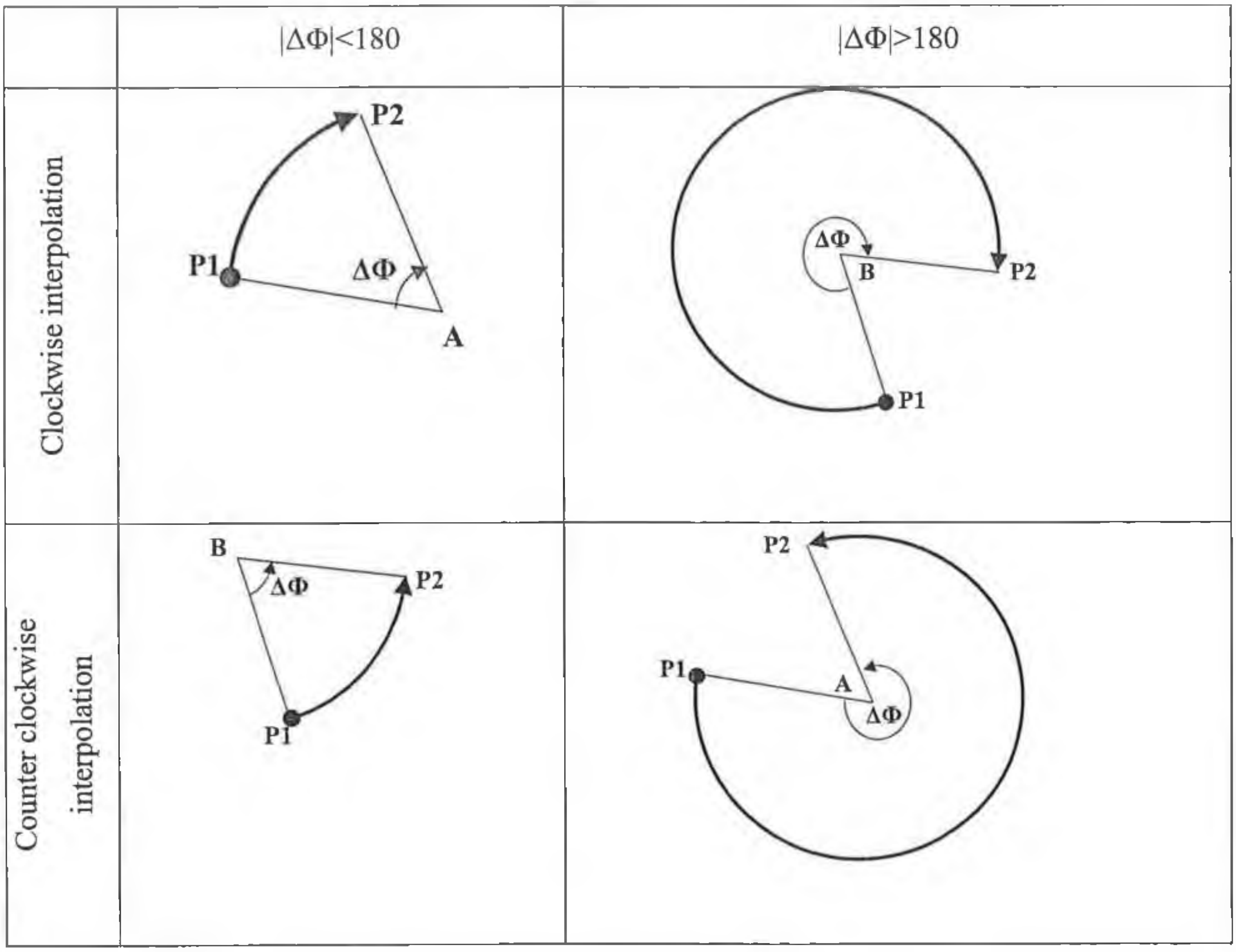


Figure 65 The four cases for circular interpolation

Observing ΔΦ

In fact the difference $\Delta\Phi = \Phi_2 - \Phi_1$ is positive for counter clockwise interpolation, and negative for clockwise interpolation. When calculating ΔΦ problems arise if the arc crosses the 0 angle see Figure 66 (c, d, g, h), which causes a miss calculation of the difference ΔΦ.

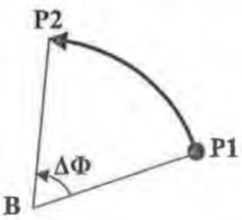
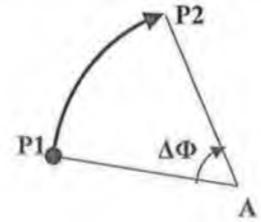
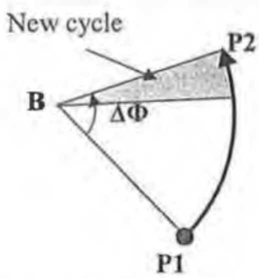
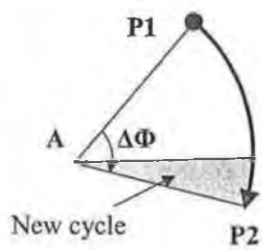
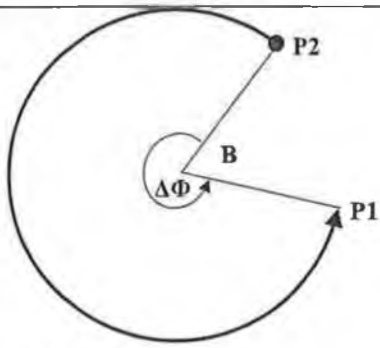
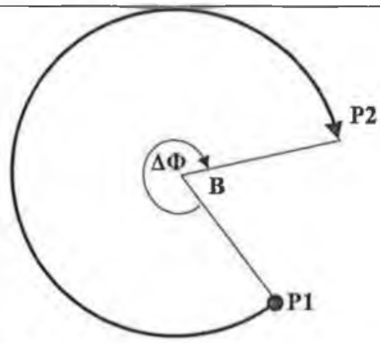
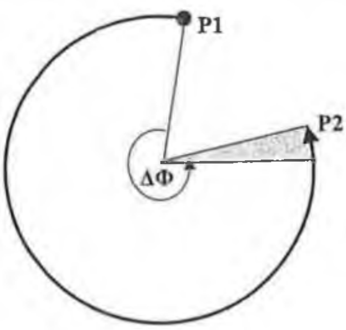
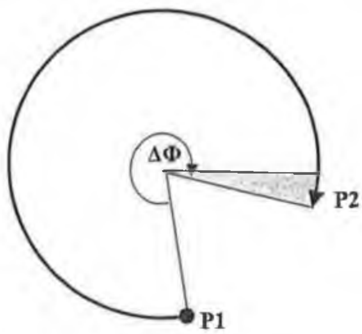
	Counter clockwise	Clockwise
Short arc in the same cycle	 a. $\Delta\Phi > 0$	 b. $\Delta\Phi < 0$
Short arc entering a new cycle	 c. $\Delta\Phi < 0$	 d. $\Delta\Phi > 0$
Long arc in the same cycle	 e. $\Delta\Phi >0$	 f. $\Delta\Phi < 0$
Long arc entering a new cycle	 g. $\Delta\Phi < 0$	 h. $\Delta\Phi > 0$

Figure 66 $\Delta\Phi$ problem

To resolve this problem 360 degrees added to Φ_2 for each centre, if the difference is negative for counter clockwise interpolation, or If the difference is positive for clockwise interpolation, 360 will be subtracted from Φ_2.

Then $\Delta\Phi$ will be calculated again for both centres (Ca,Cb) in clockwise or counter clockwise, the absolute value $|\Delta\Phi|$ for one centre is bigger than 180 for one direction and less than 180 for the other direction; the algorithm will decide which centre is right for the interpolation based on the given information See Figure 67 for the algorithm, and Appendix D3 for the code.

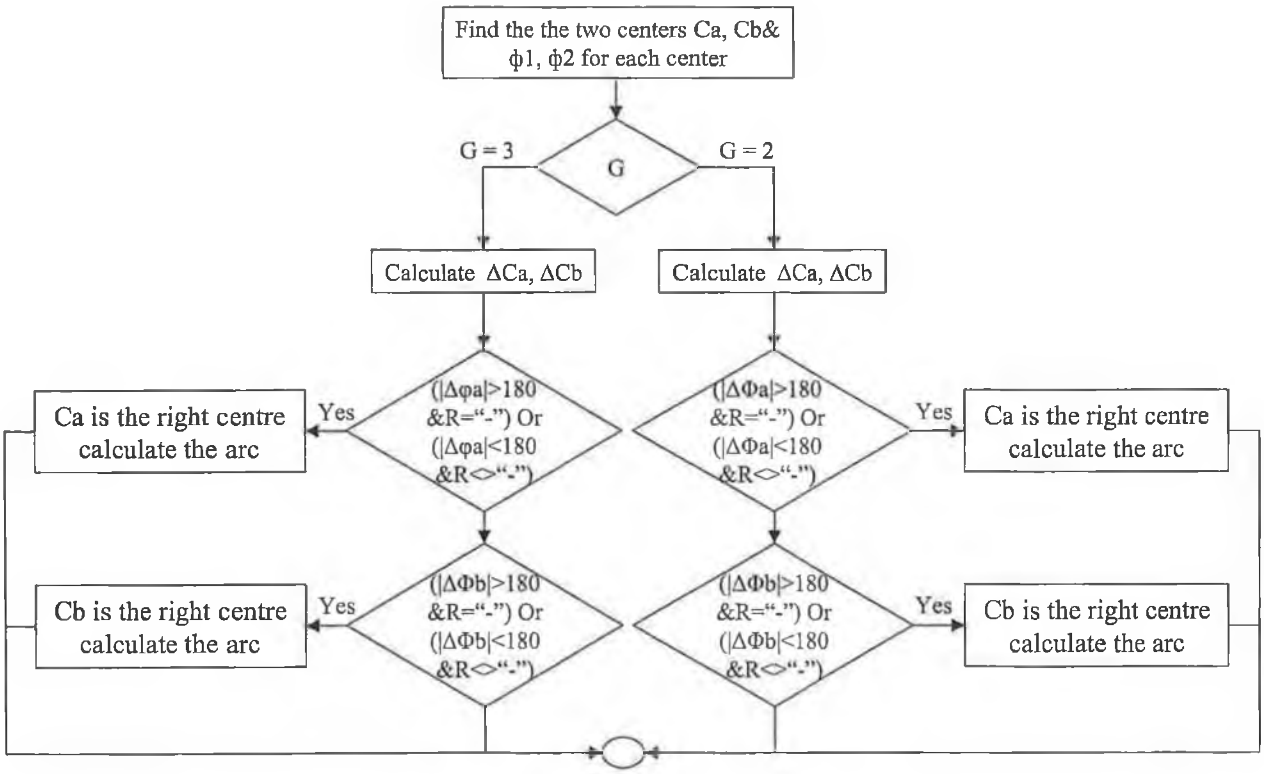


Figure 67 flow chart to find the right centre for the interpolation

After deciding which is the centre of the arc, the arc drawn starting from the starting position to the end position, the distance between the points on the arc Lc see Figure 68, equal one by default and can be changed using the option menu. by minimizing the value of Lc, smaller steps will be calculated, using equation 19, and more steps will be on the curve, which means smother curve will be obtained.

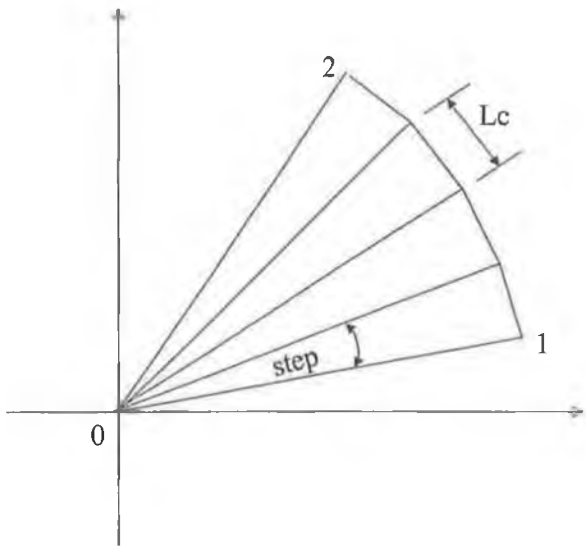


Figure 68 chord length for one step angle

$$step = \frac{180Lc}{\pi R} \qquad \textit{Equation 20}$$

Where Lc is the chord length for one step angle.

c. Drawing the CNC Tool Path

To draw on the screen, first the screen has to be scaled, using the max values for x and y, the program reads "outfile3"file which contains the entire tool path in linear displacement only and draws the tool path on the screen using the line command {Picture1.Line (x1, y1)-(x2, y2)} see Appendix D4 for the code. This will give the operator the chance to check if there are any mistakes in reading the CNC code. If the result is satisfied the operator continue to the next step.

d. Simulate

To simulate the deposition of wax the algorithm start by opening the "outfile3". The program reads G, X, and Y computes the total displacements in x and y direction then calculates the total travelling distance D_t.

$$D_x = x_2 - x_1 \qquad \textit{Equation 21}$$

$$D_y = y_2 - y_1 \qquad \textit{Equation 22}$$

$$D_t = \sqrt{D_x^2 + D_y^2} \qquad \textit{Equation 23}$$

If G-code is not "G0", then wax must be deposited and the travel length along each segment must be divide by the droplet diameter.

There are three categories for the answer, which must be considered when building the PC23 code, see Appendix D5 for the code.

Case 1: (D_t) is smaller then the wax diameter (D) read the next position and repeats the comparison.

Case 2: (D_t) is equal to (D) move to (x2, y2).

Case 3: (D_t) is greater then (D) divide the interpolation into steps equal to (D).

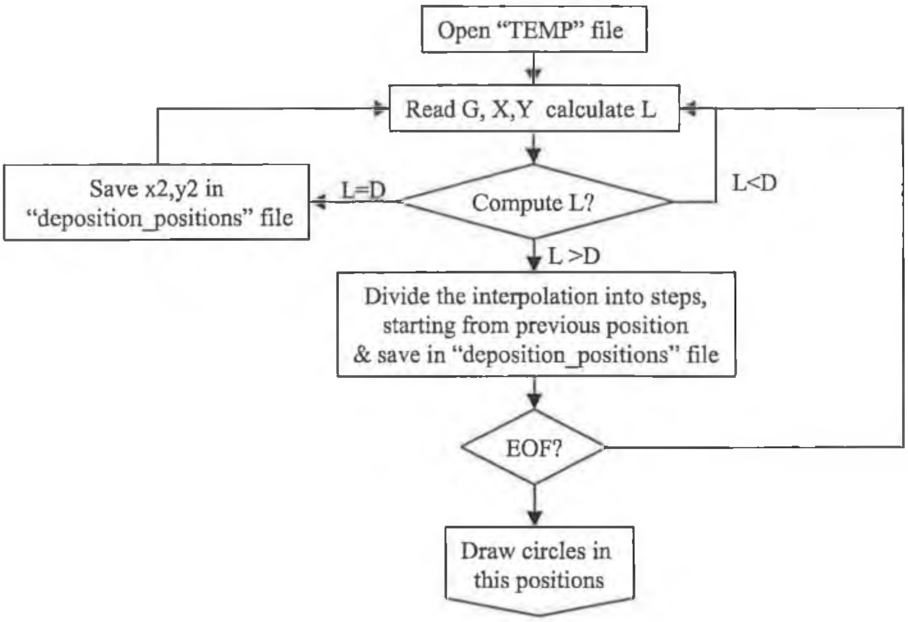


Figure 69 CNC/RP simulation algorithm

If the total travelling distance is greater than the droplet diameter, the motion has to be divided into a number of movements by dividing the total travelling distance by the droplet diameter. The number of movements must be an integer value, which, means if the fraction of the division is more then half of the diameter additional droplet will be added, if the fraction is less then half of the diameter no deposition will be added. After deposition of the last droplet for one segment the program continues to move to the third point using the second fabricated point (2`) as starting point instead of using the second point (2) see Figure 70. All of these positions will be saved in file "outfile5"

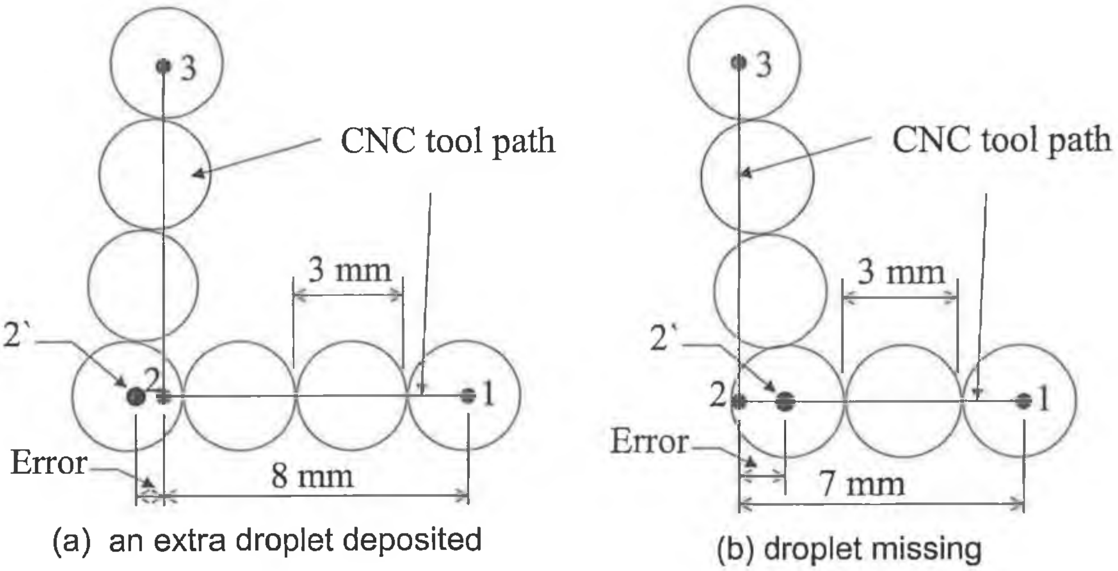


Figure 70 Error due to moving from fabricated point

e. Correction:

It is noted that some of the voids and geometric errors will accrue using the above technique. This problem can be avoided by starting the new movement from the new position (2), not from the fabricated point (2`) see Figure 71. The program simulates the deposition of wax after correcting the path. See Appendix D5 for the code.

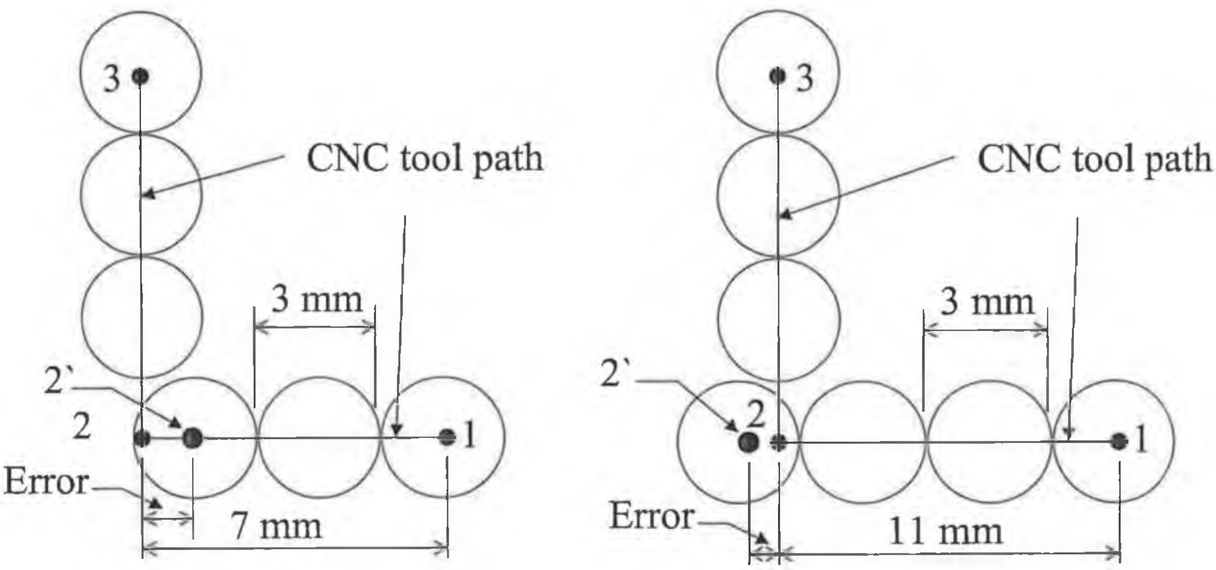


Figure 71 Starting the new movement from the original last position

f. Filtering.

A Filtering operation can be executed by selecting “Filter” command from Run menu or by clicking on filter button Figure 60. Filtering operation is performed to eliminate the additional deposition of material. Filtering can be done with different factors. Increasing this value will eliminate more deposition points.

The process proceeds by transferring the first point from “outfile5” file into “outfile6”, then picking the next point from “outfile5” and determine the distance between this point and the previous points in “outfile6”, if the distance is bigger than the checking value the program will save this point in “outfile6”, if not the program omitt this point. The program continues to check all the deposition positions by scanning “outfile6” for each point in “outfile5”, CNC/RP simulates the omitted points in different colour on the screen see Appendix D6 for the code.

g. Build the instruction command file for PC23

Build operation can be executed by selecting “Build” command from Run see Figure 60. Build command builds the instruction commands in X-language to operate PC23 indexer. The instruction command will be formulated according to the last function (simulate, correction or filtering)

The same algorithm in CAD/RP programme is used here, see section 0.

h. Save

The Save command from file the menu will call the save dialogue box to save the command strings file in a text file. The same form was also used in CAD/RP see 0

Chapter 5 Result And Discussion

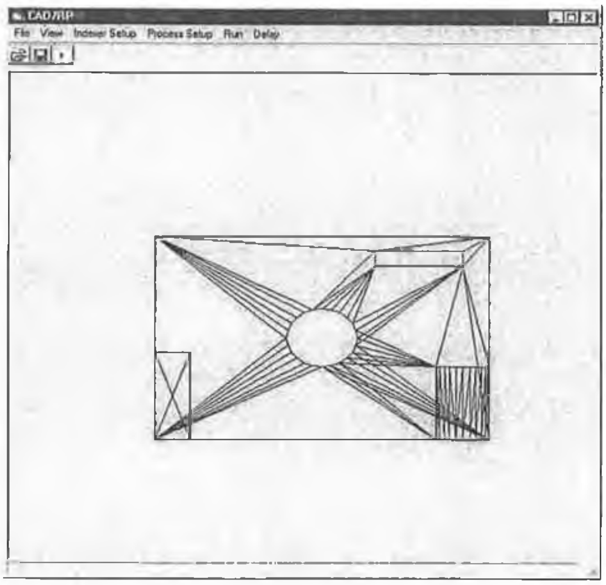
This chapter is devoted to the analysis and discussion of the outcomes and performance of the developed software. Section 5.1 describes CAD/RP capabilities and all the required steps to generate the RP instructions command file. Section 5.2 describes CNC/RP software capabilities and its performance. Section **Error! Reference source not found.** illustrate the development in the CAM/RP program which controls the wax depositing RP system. Many parts were fabricated using this wax droplet RP system using the data obtained from CNC/RP.

5.1 CAD/RP

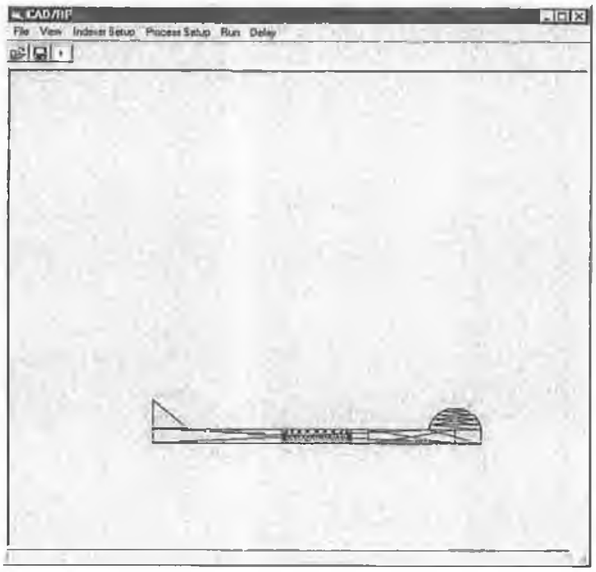
CAD/RP proved the capability to process and slice STL files, generate the tool path for RP operation and constructs the instruction commands for the PC indexer. The entire progress through the steps can be visually displayed and controlled in CAD/RP.

5.1.1 View Geometry

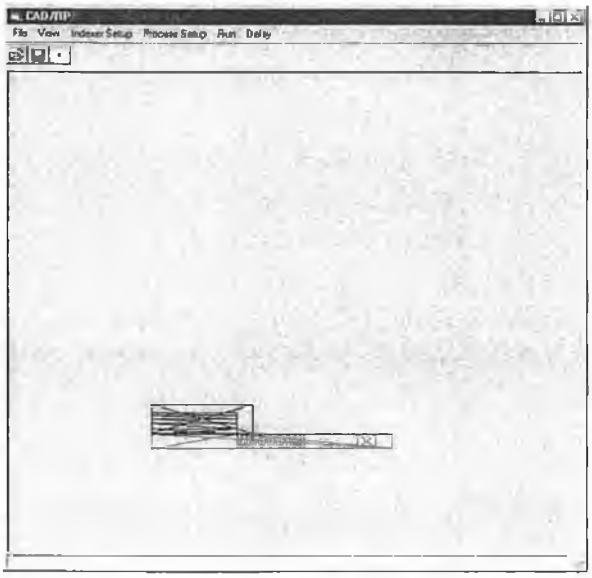
CAD/RP provides capability to view the design in 2D and 3D. This gives the ability to ensure that the right design is imported before starting the slicing process. CAD/RP views the model in x-y, x-z, y-z and 3D coordinate systems, see Figure 72.



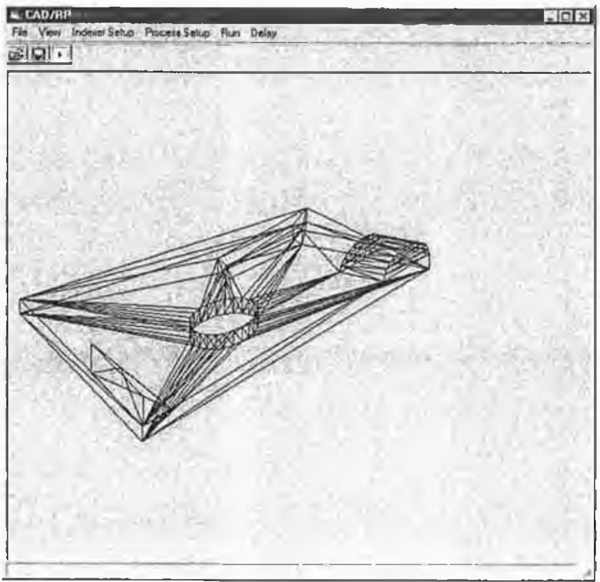
(a) X-Y coordinate system.



(b) X-Z coordinate system



(c) Y-Z coordinate system

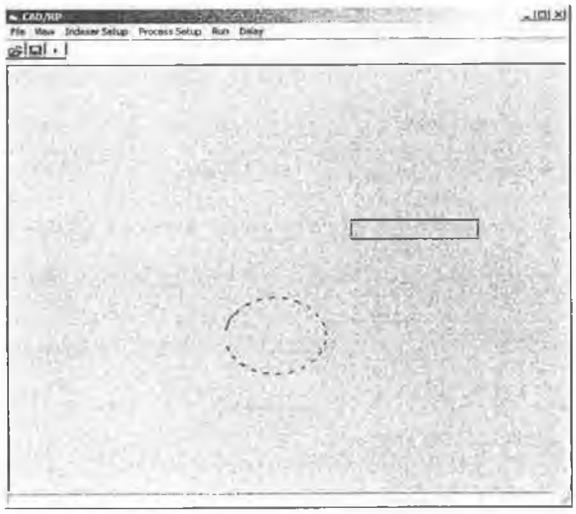


(d) 3D coordinate system

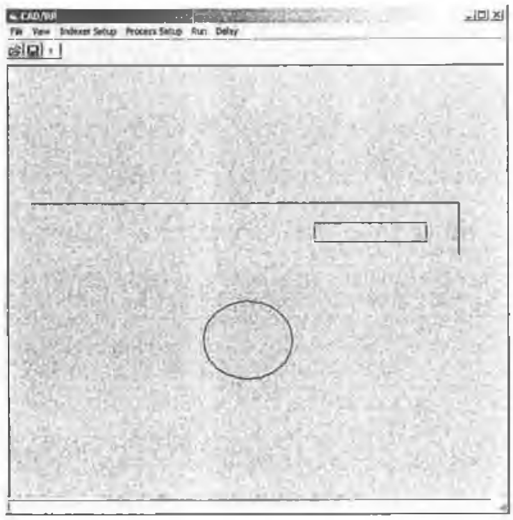
Figure 72 Various views for the imported design in CAD/RP.

5.1.2 Slicing process

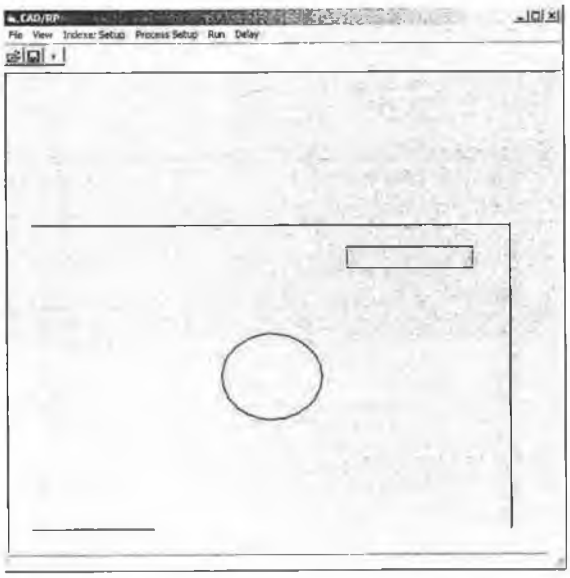
CAD/RP is capable of slicing any STL file with any layer thickness. The result of this operation is a random segment order contour. When a long delay time is specified a random construction of the contour can be observed see Figure 73.



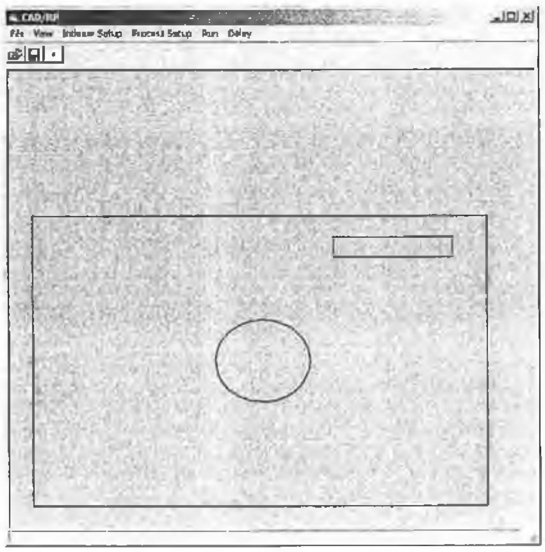
(a) 25% of contour



(b) 50% of contour



(c) 75% of contour

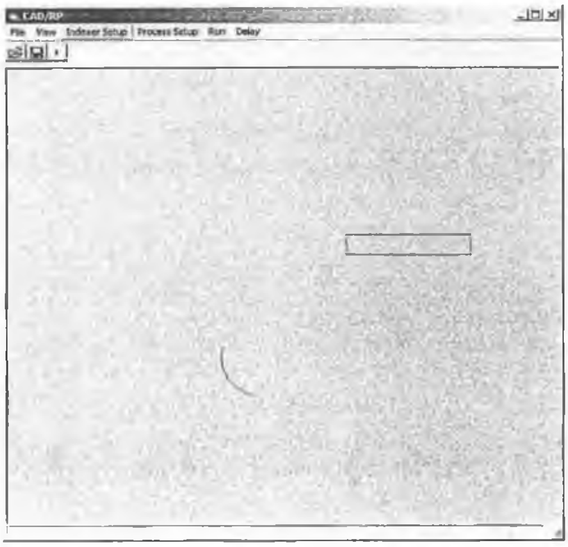


(d) 100% of contour

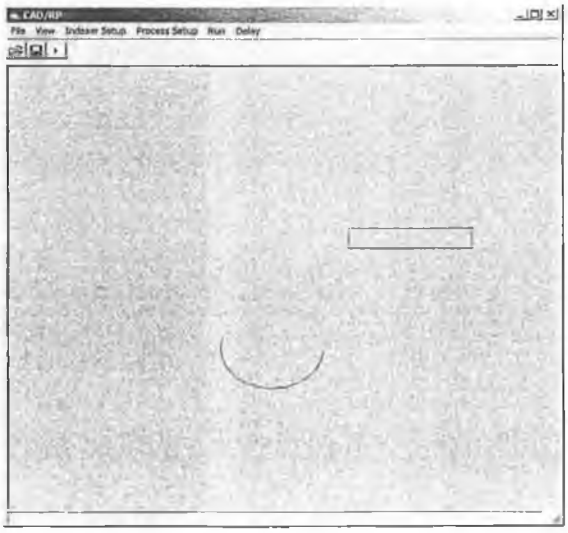
Figure 73 Construction of contour as found in STL file

5.1.3 Contour Construction

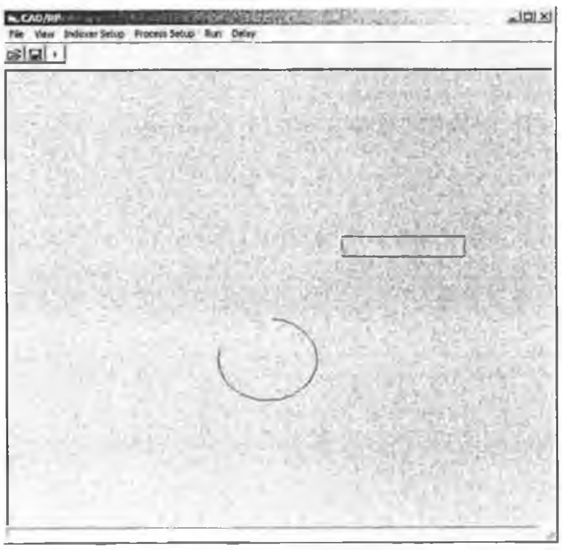
CAD/RP orders the contour in this step to construct a continuous tool path. It is very clear to see the importance of this step, especially when circular contour is constructed see Figure 74.



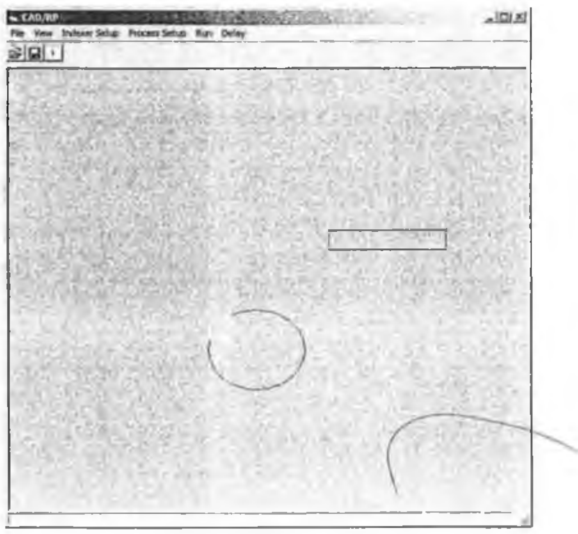
(a) 20% of contour



(b) 50% of contour



(c) 75% of contour

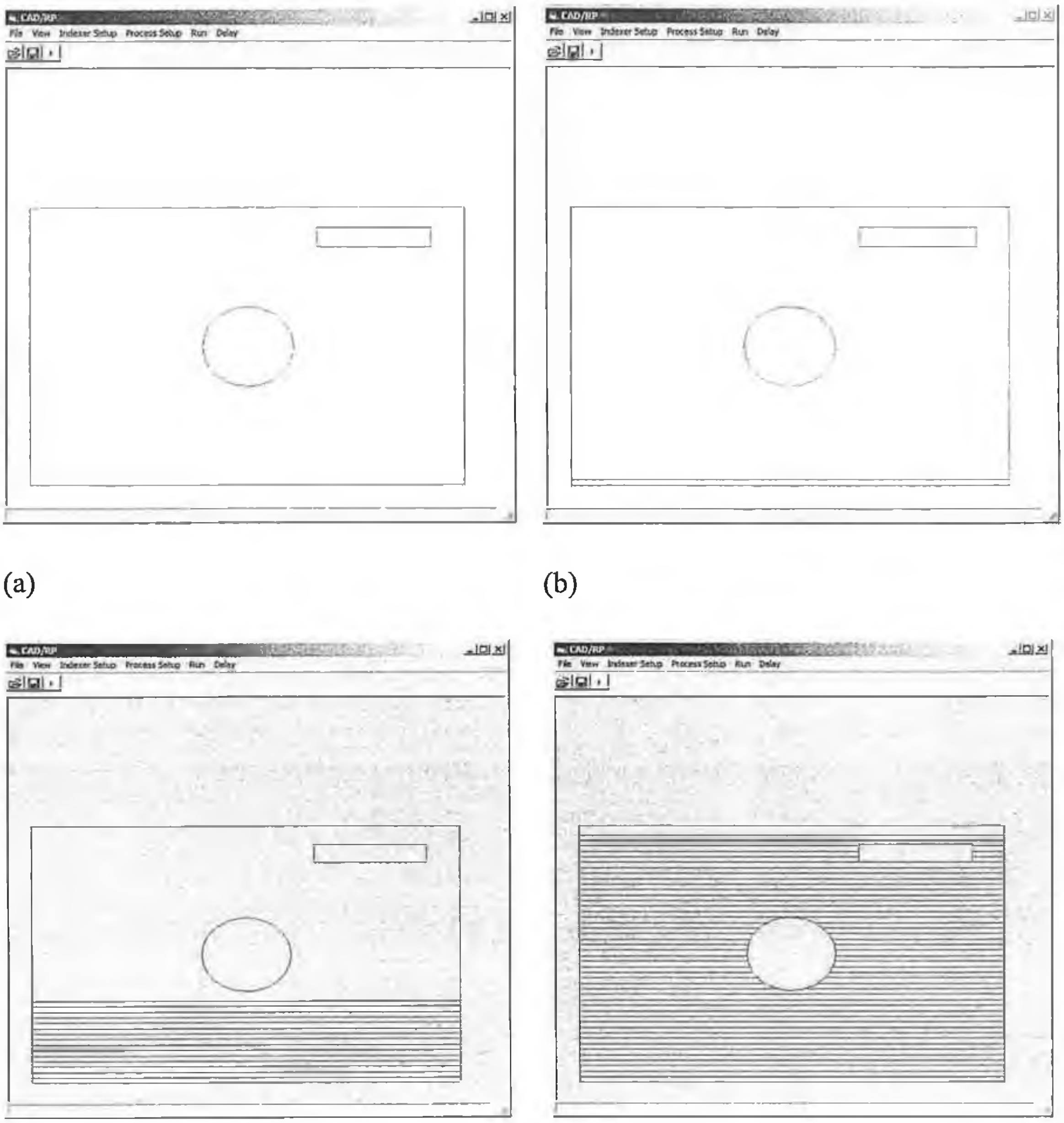


(d) 100% of contour

Figure 74 Construction of contour as found in STL file

5.1.4 Filled Pattern

CAD/RP fills the cross section area with a raster filling style, this can be seen in Figure 75 recognizing the cavity inside the geometry and filling only the solid areas.



(a) (b) (c) (d)

Figure 75 Raster scan pattern filling

5.1.5 Simulation of wax deposition

CAD/RP can simulate the deposition of wax starting by building the contour then the cross-section area, see Figure 76. As seen in Figure 77 when the repositioning reaches the end of geometry it reverses the direction to speed the deposition operation.

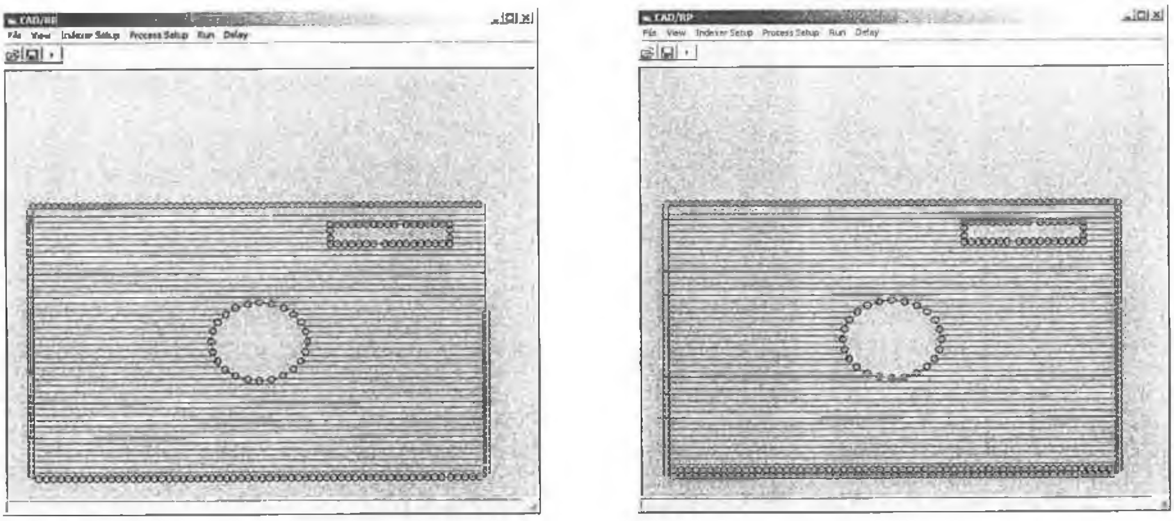


Figure 76 Building the contour

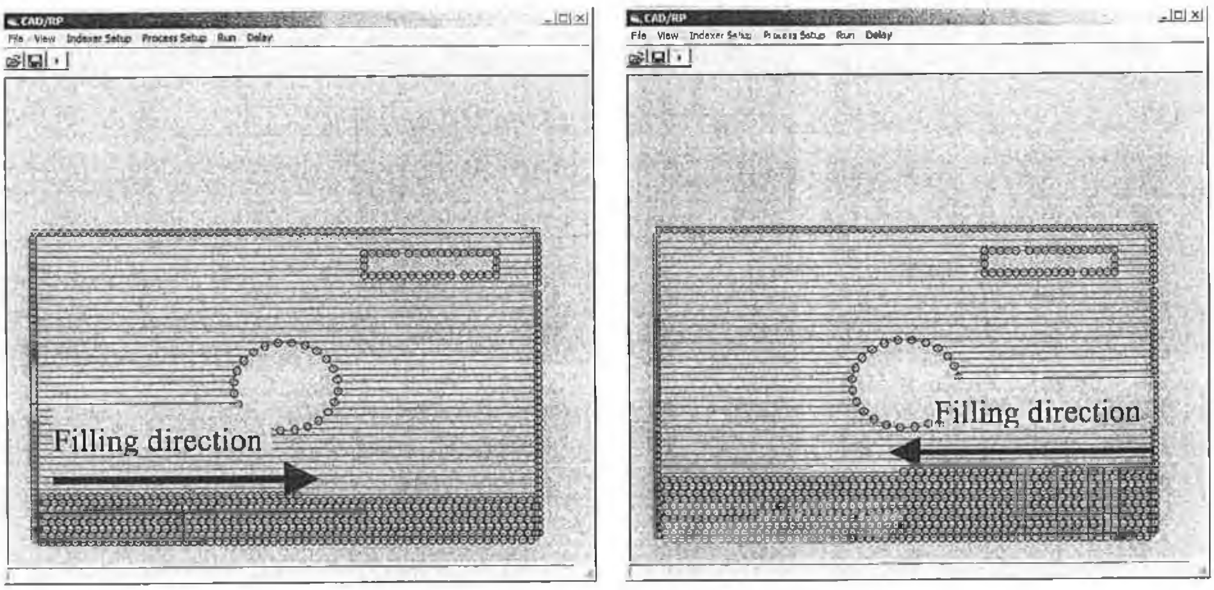


Figure 77 Building the cross-section area

5.1.6 Build the instruction command file

After simulating the deposition of wax, and simulation was satisfied, the instruction command file can be built by selecting the build command. CAD/RP builds the instruction command in a very big reduction of time. The previous geometry contains 112 facets, and the instruction commands was built in 2.52 second and contains 30,450 commands, it could take several days to write these commands manually, this confirms the significance of developing CAD/RP program for the wax droplet RP system.

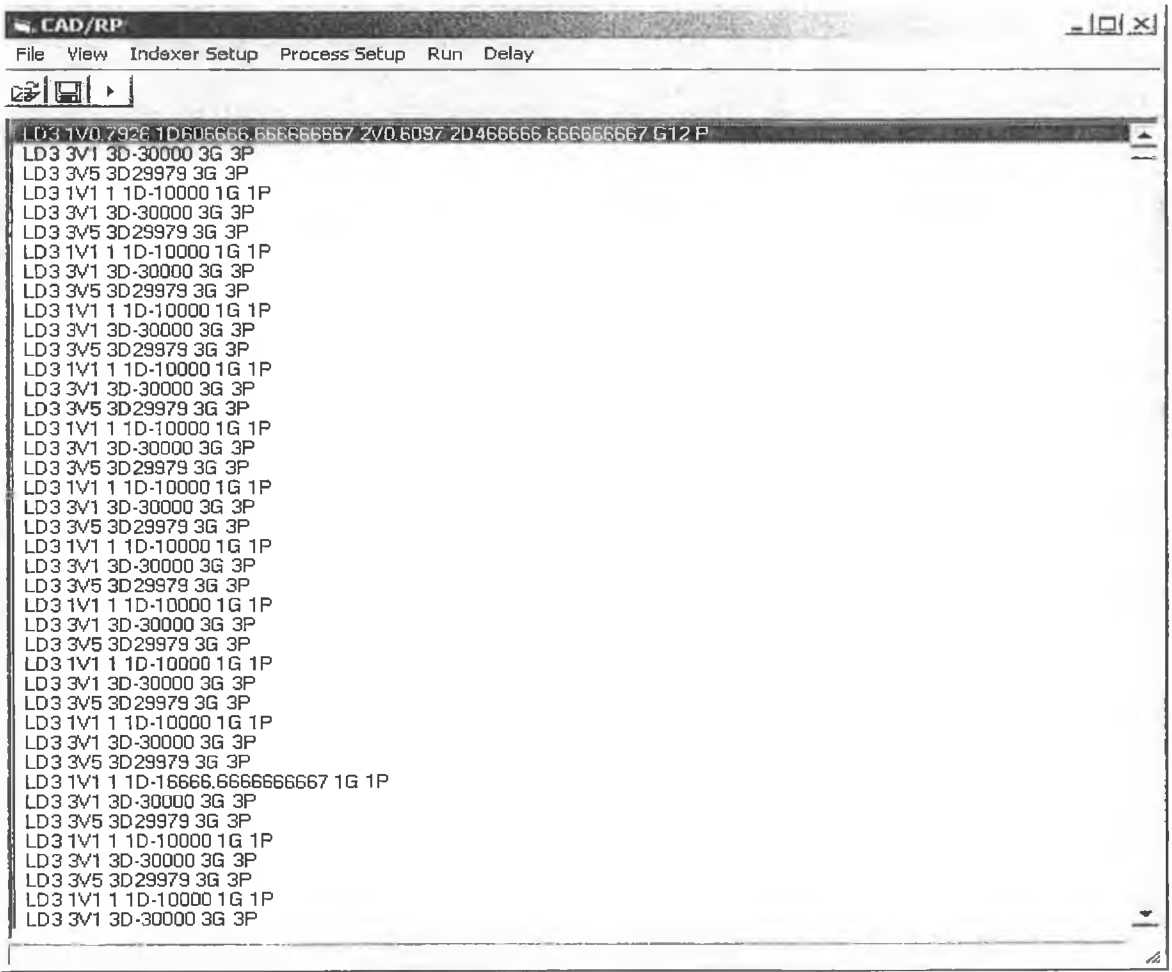


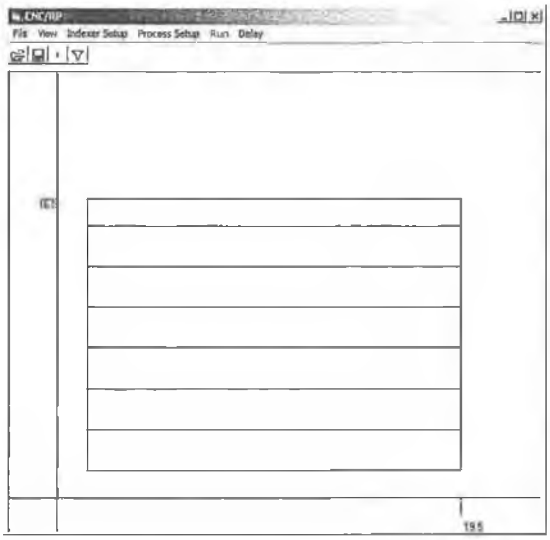
Figure 78Instruction command for CAD/RP

5.2 CNC/RP

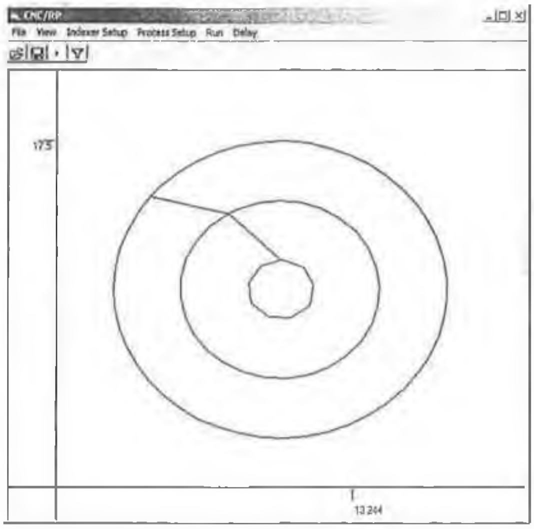
CNC/RP provides the capability to process the CNC code and create the instruction commands for the PC indexer. The entire performed steps can be visually displayed and controlled in CNC/RP.

5.2.1 Demonstrate CNC tool path:

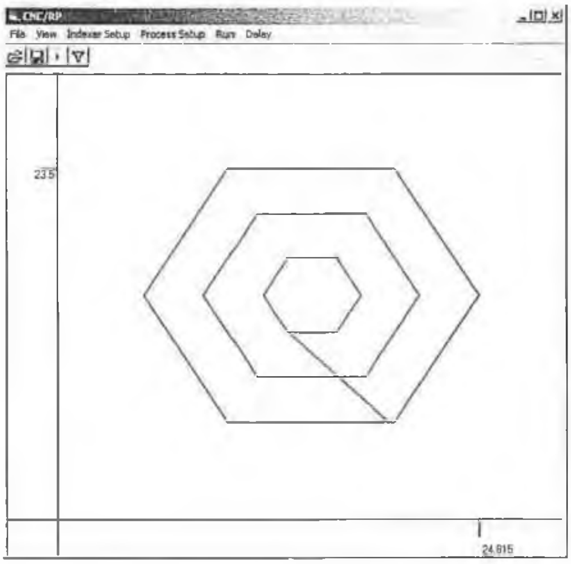
The program was able to read the CNC code and demonstrates the tool path, which was generated in the AlphaCAM system, it provides the capability to observe any type of motion in CNC language see Figure 79. This step is very important to detect any mistakes in reading the CNC code, and to ensure that the tool path is suitable for RP process.



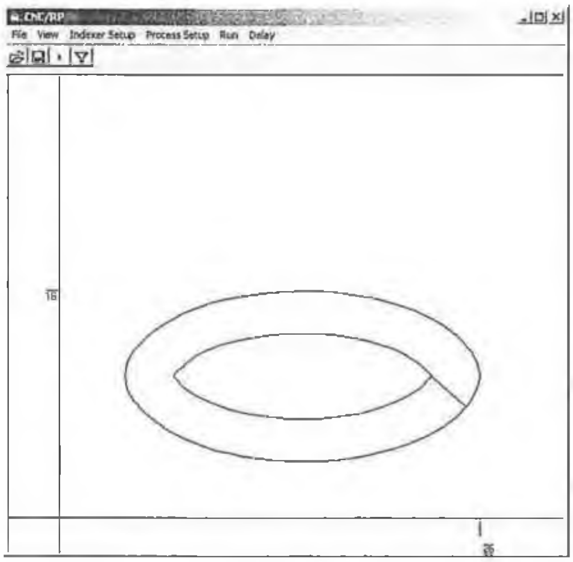
a. Rectangular



b. Cylinder



c. Polygon



d. Ellipse

Figure 79 Drawing the CNC tool path for different parts

5.2.2 Simulate the deposition of wax

After displaying the tool path, the program simulates the deposition of wax with the required deposition diameter see Figure 80. This is also a very important step to ensure that the tool path is suitable for the RP process.

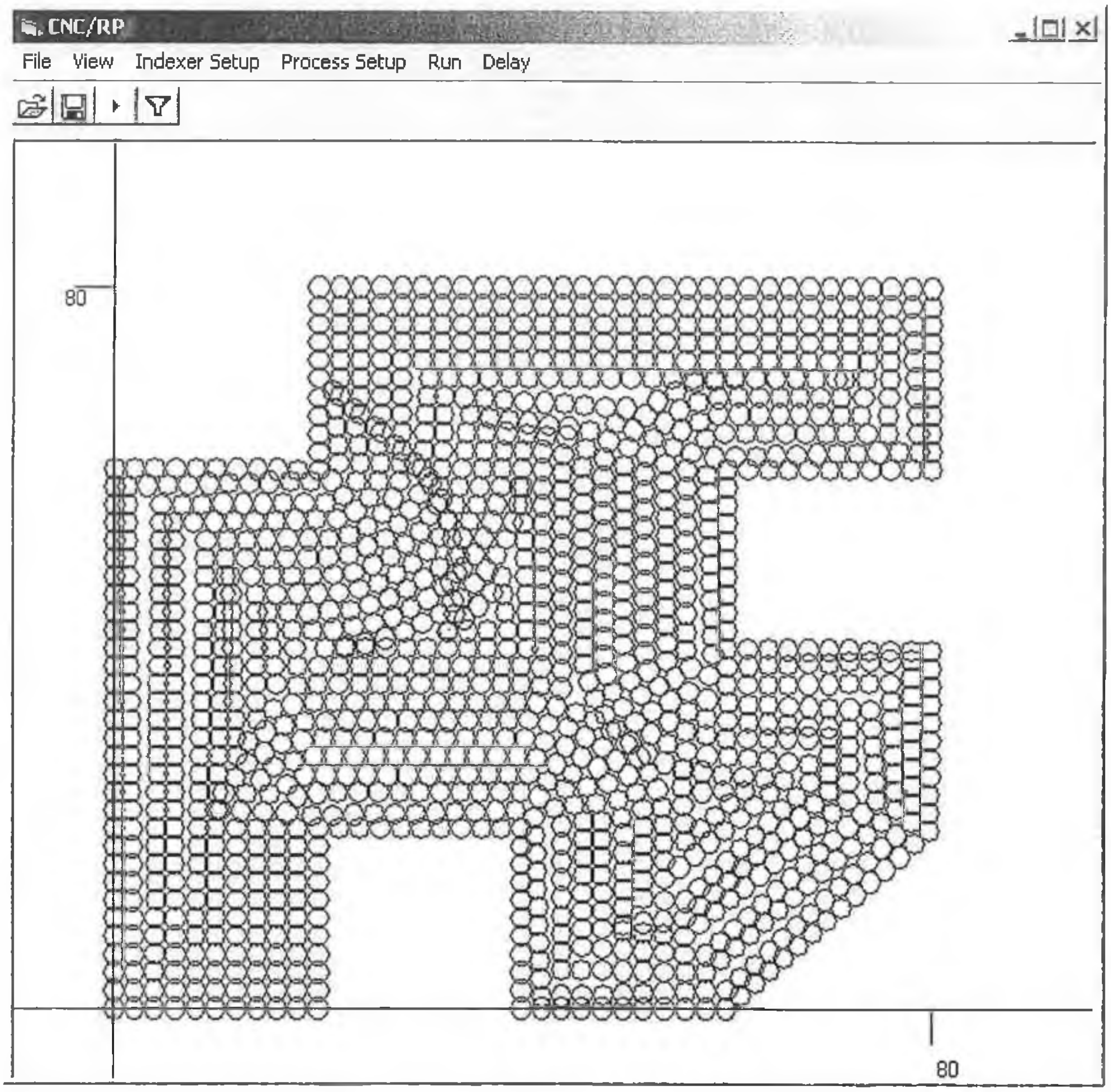


Figure 80 Simulating the deposition of wax

There were some problems raised when using the machining tool path for additive rapid prototyping. These problems were:

a. Multiple depositions: In machined operations the problem of repeat-machined areas is no problem and does not affect the part. In the additive operation this will cause additional material in the same place, which causes an undesired shape.

9. Voids and Geometric Errors due to droplet size: this problem was discussed in section 4.4.5e. Figure 81 illustrates this problem, if this problem arises a correction algorithm must be used to eliminate this problem

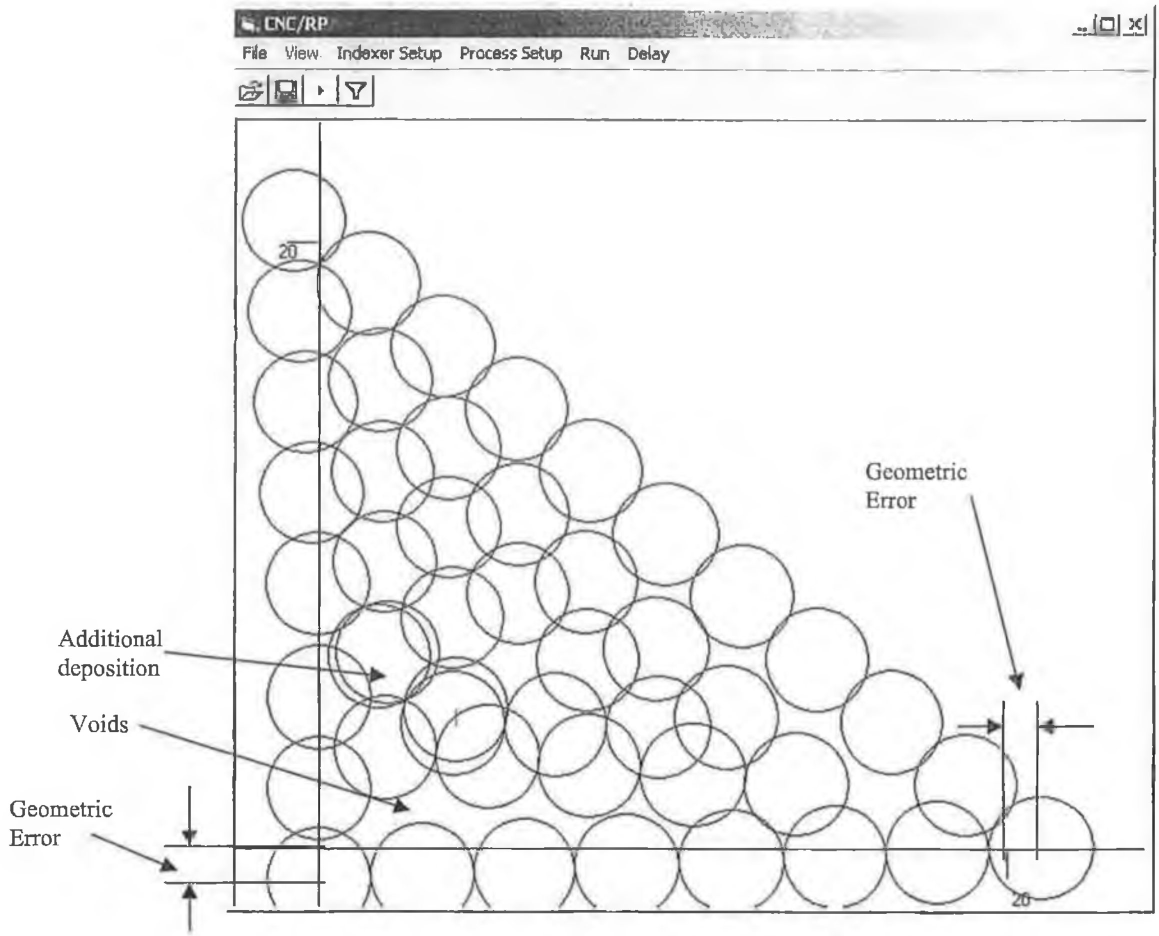
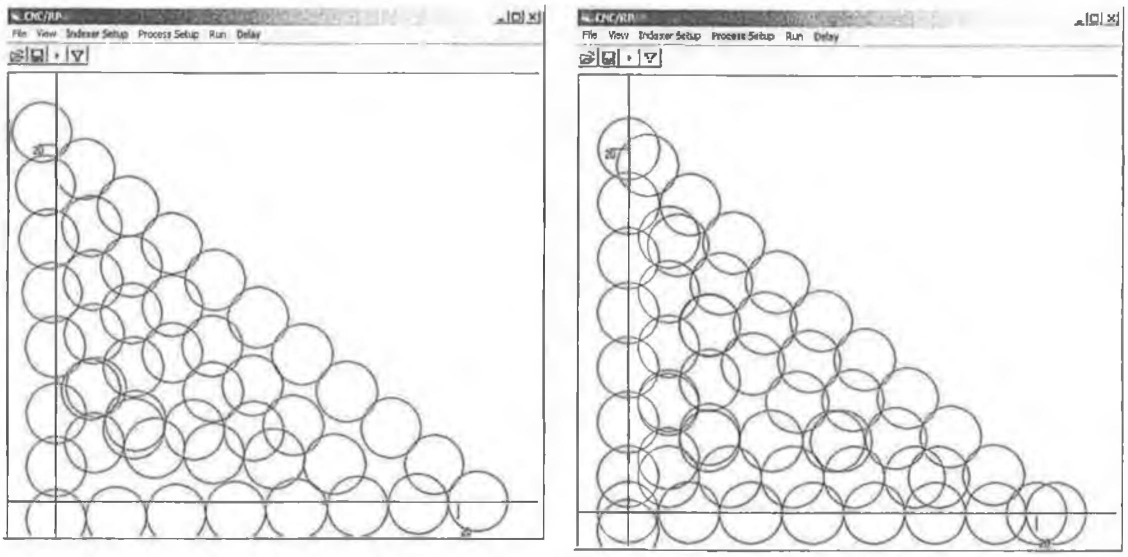


Figure 81Figure 81 Voids and Geometric Errors

5.2.3 Correction

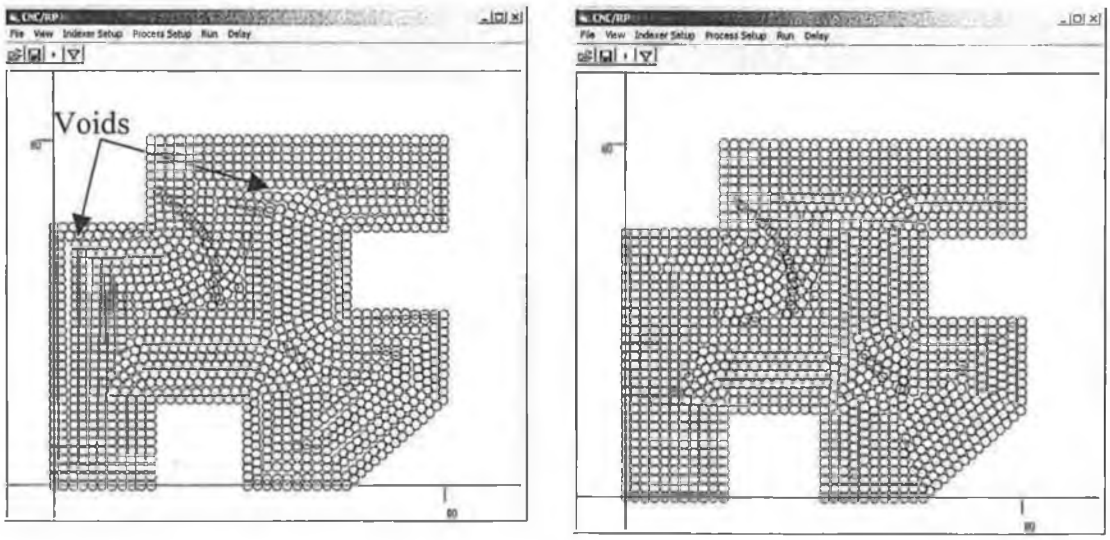
It is noted that some of the Voids and Geometric Errors, which mentioned above, could be avoided by using correction algorithm see 4.4.5e. Figure 83 show the simulation after correcting the paths.



a. *Before correction*

b. *After correction*

Figure 82 The simulation before and after correcting the tool path



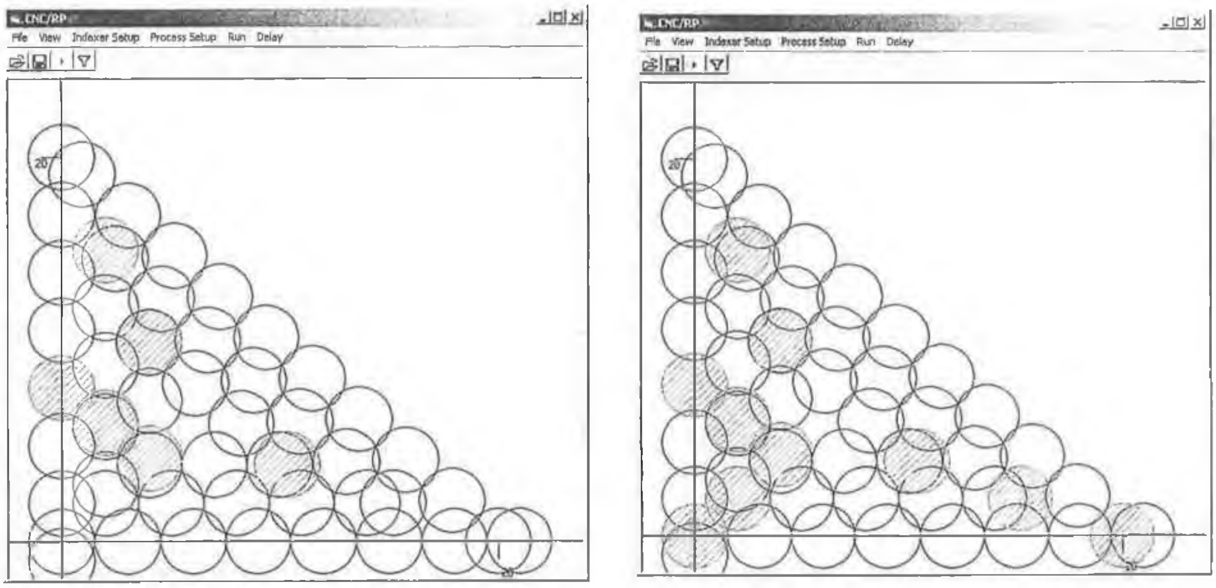
a. *Before correction*

b. *After correction*

Figure 83 The simulation after correcting the tool path

5.2.4 Filtering

The filtering operation is performed to eliminate the additional deposition of material by cancelling all the extra deposition positions. Filtering can be done with different factors. Increasing this value will eliminate more deposition points see Figure 84.



a. Filtering with 1mm *b. Filtering with 1.2 mm*

Figure 84 Filtering operation with different factors

5.2.5 Build the instruction command file for PC23

The programme generates the motion code and the deposition code for the PC23 see Figure 85. Once the user is satisfied with the deposition pattern the instructions can be saved, the instruction command file can be built by selecting the build command from Run menu. CNC/RP builds the instruction command in a very big reduction of time. The geometry in Figure 80 contains 216 line of G-code, and the instruction commands was built in 6.46 second and contains 4,014 commands.

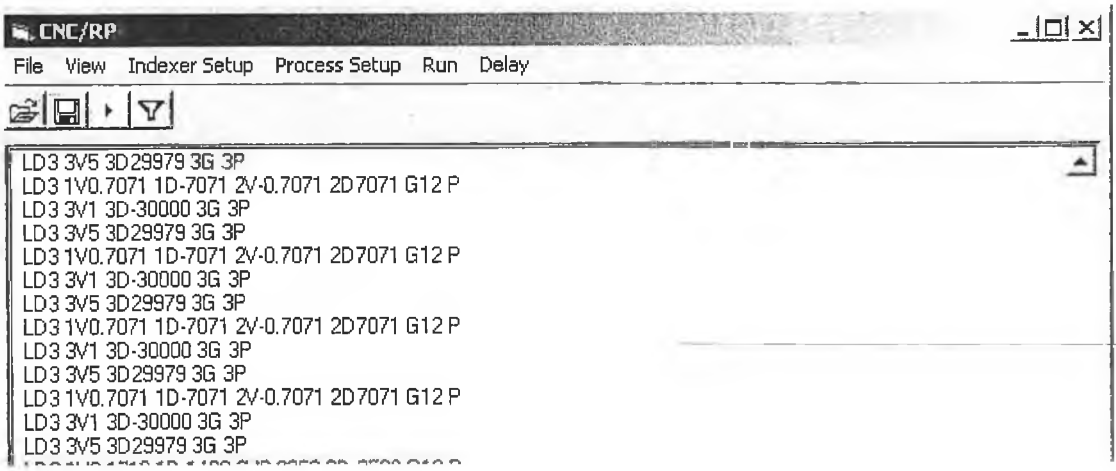


Figure 85 Motion code for the PC23

5.3 Shapes fabricated using Wax Droplet RP System and CNC/RP.

Many parts were fabricated using the data obtained from CNC/RP, The wax was heated to 82°C and deposited with Wax Droplet RP System.

5.3.1 Polygon shape

To design this part in AlphaCAM select special geometries from the geometry pull down menu then select polygon, enter 6 for the Number of Sides, 20 mm for the Diameter of Describing Circle and select outside option then click Ok.

Some parameters for tool path generation

Tool	Flat 3mm 2F EC HSS
Tool Directions	CW
Pocketing Type	Contour
Start Cutting at	Outside
Final Depth	-6 mm
Number of Cuts	3
Width of Cut	3 mm

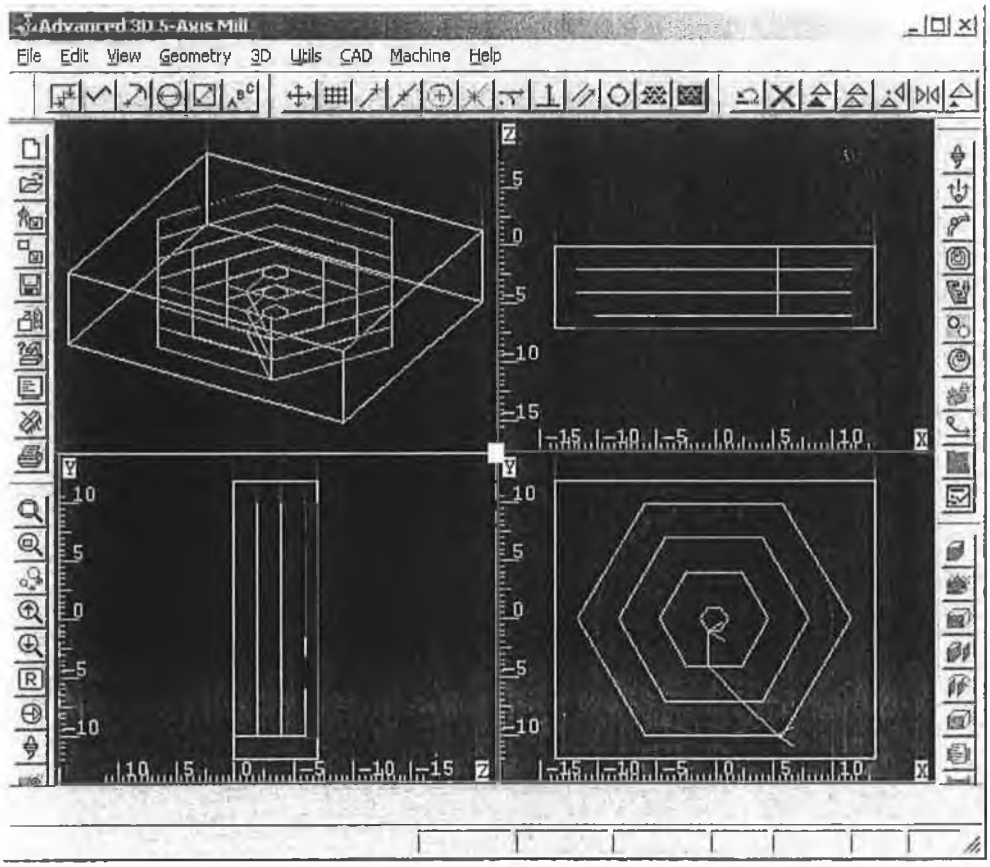


Figure 86 Tool path generated in AlphaCAM for Polygon shape

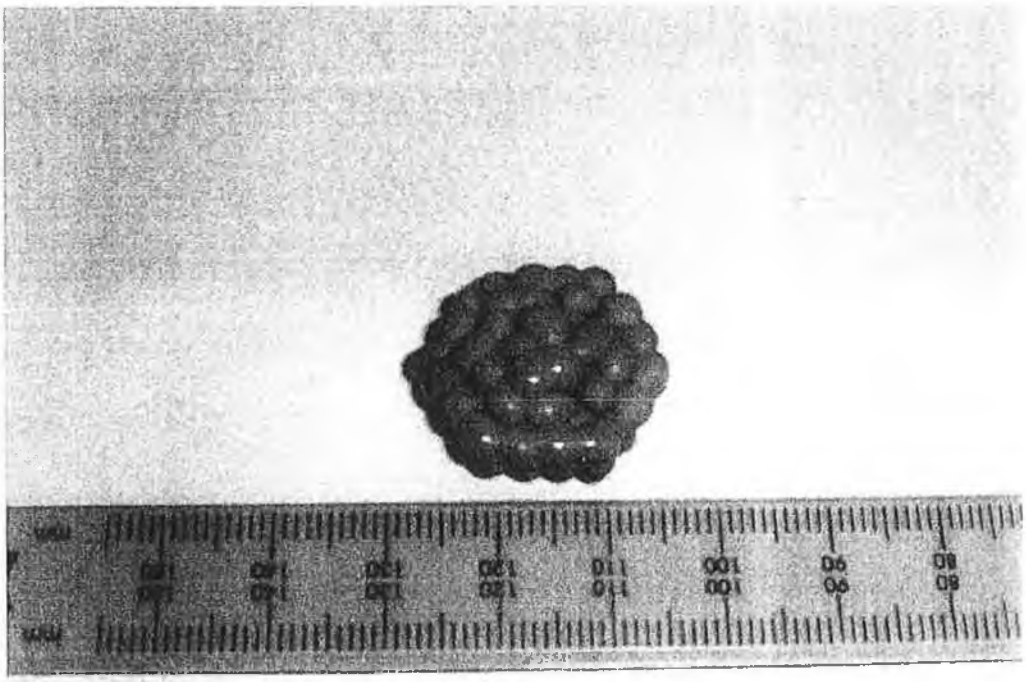


Figure 87 Polygon shape deposited using Wax Droplet RP System

5.3.2 Ellipse shape

Select special geometries in AlphaCAM from geometry pull down menu then select polygon, enter 25 for the Width, 15 mm for Height, 4 for the Number of Quadrants and 4 for the Number of Arcs per Quadrant. then click Ok.

Some parameters for tool path generation

Tool	Flat 3mm 2F EC HSS
Tool Directions	CW
Pocketing Type	Contour
Start Cutting at	Outside
Final Depth	-6 mm
Number of Cuts	3
Width of Cut	3 mm

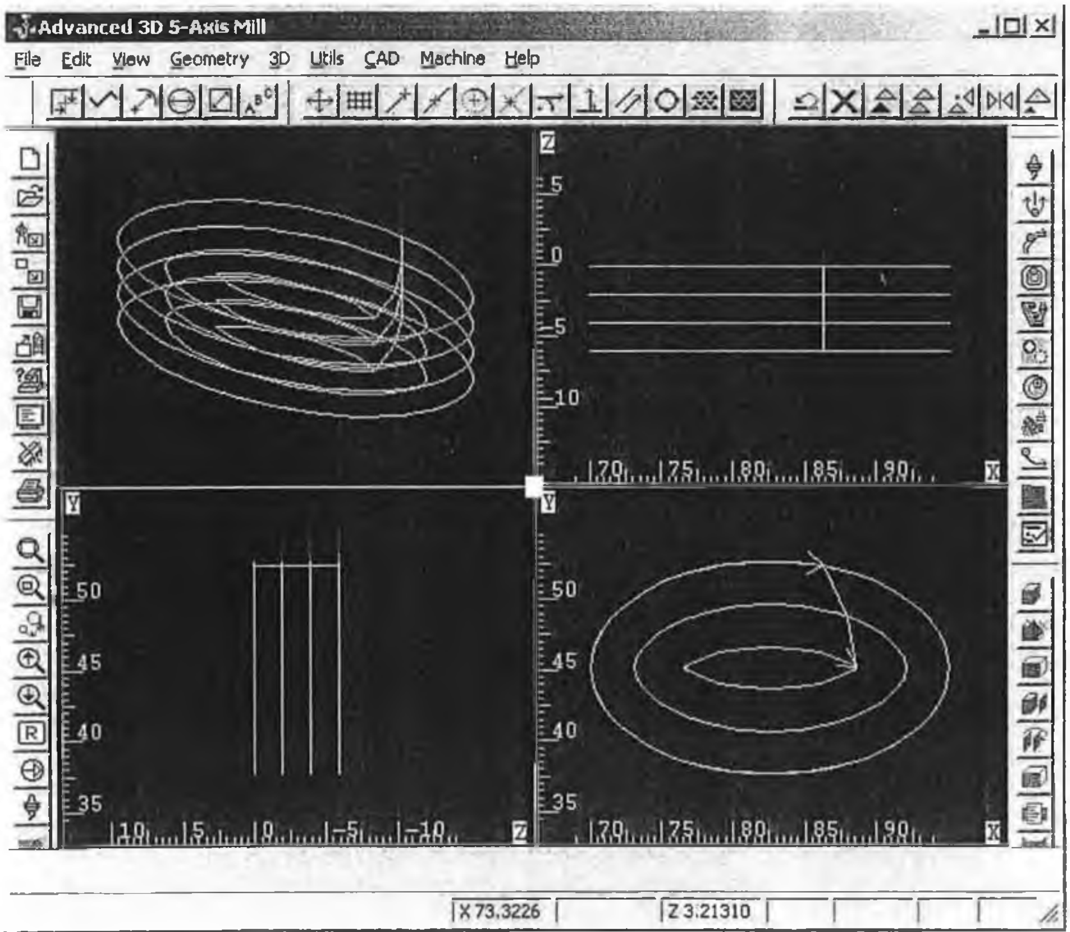


Figure 88 Tool path generated in AlphaCAM for an Ellipse shape

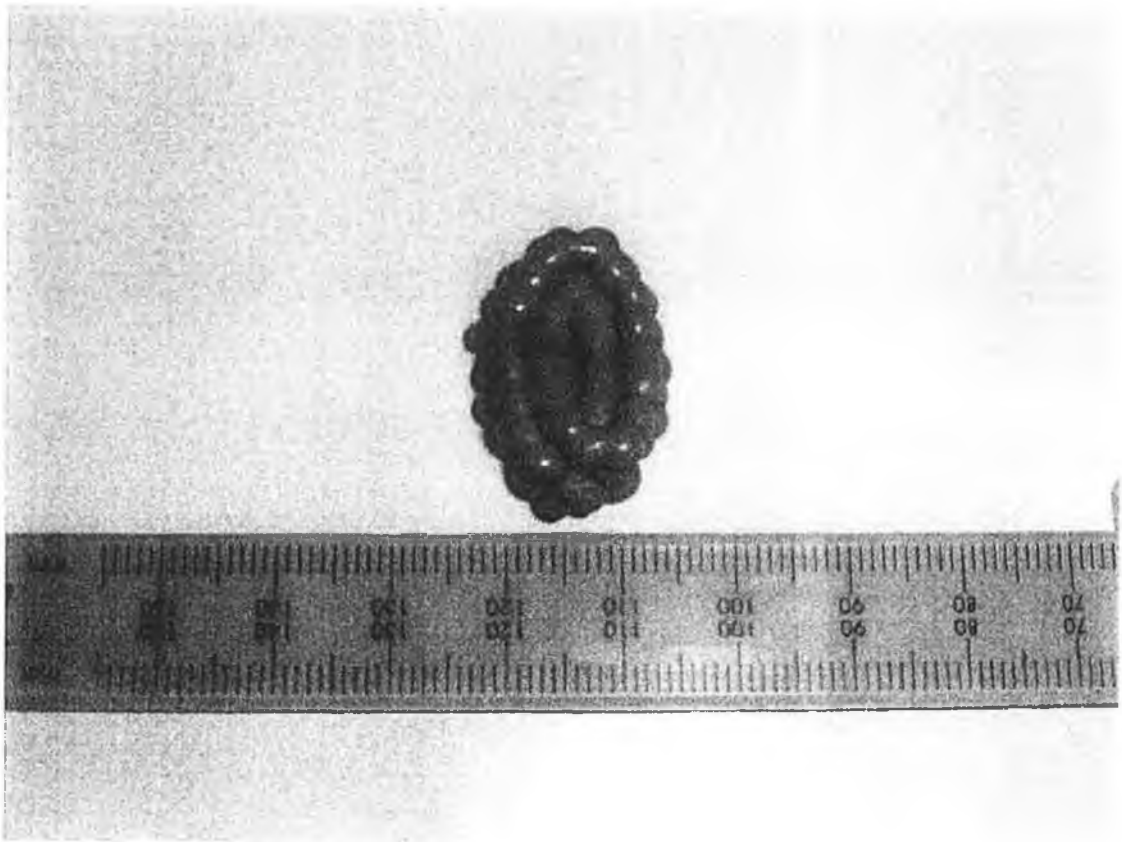


Figure 89 Ellipse shape deposited using Wax Droplet RP System

5.3.3 Cylinder shape

In AlphaCAM select circle from geometry pull down menu then select Centre and diameter, enter 15 mm for the diameter, enter (15,15) for the centre of the circle.

Some parameters for tool path generation

Tool	Flat 3mm 2F EC HSS
Tool Directions	CW
Pocketing Type	Contour
Start Cutting at	Outside
Final Depth	-6 mm
Number of Cuts	3
Width of Cut	3 mm

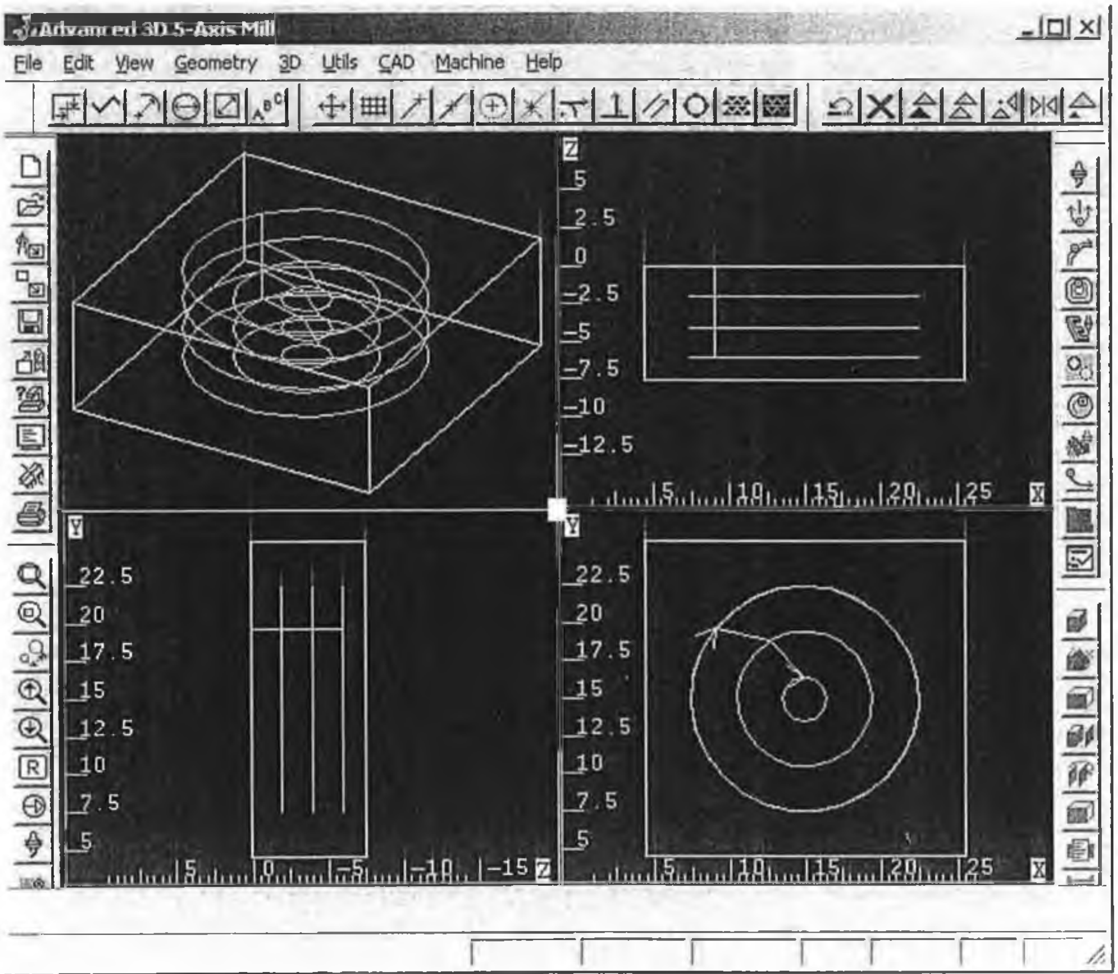


Figure 90 Tool path generated in AlphaCAM for a Cylinder shape

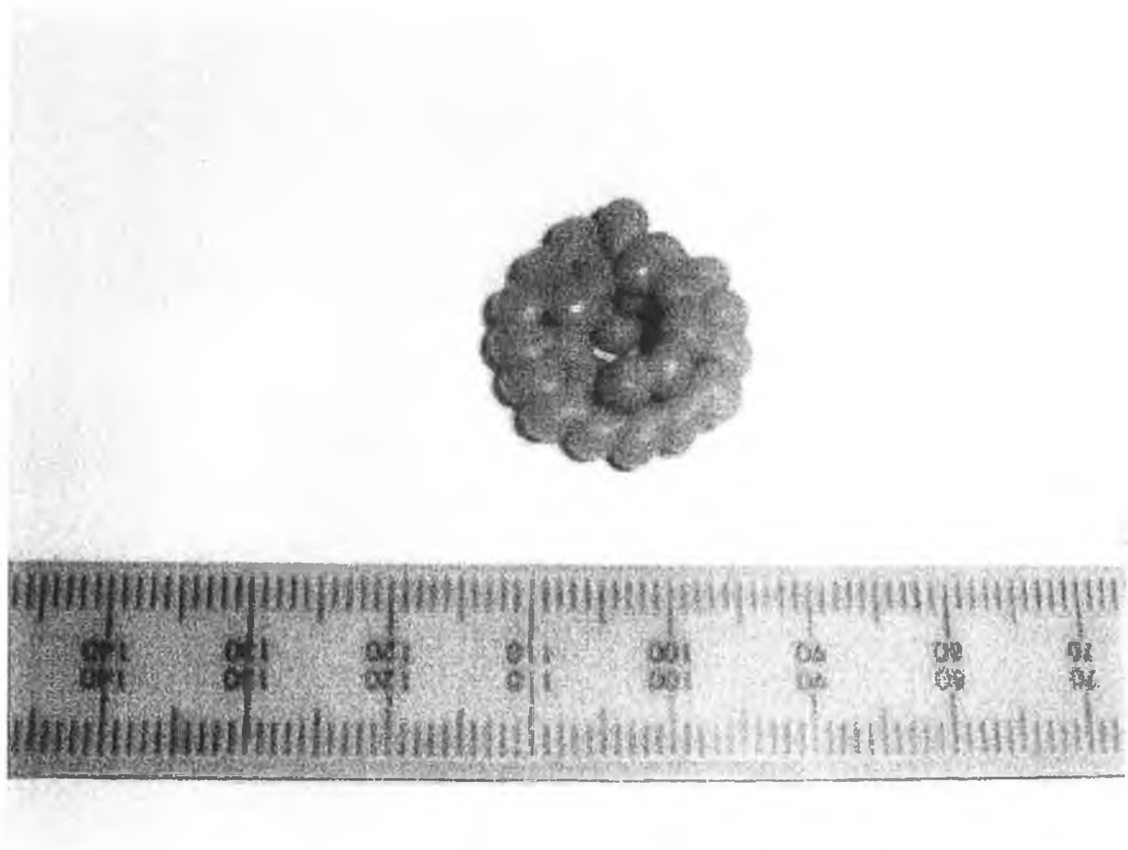


Figure 91 Cylinder shape deposited using Wax Droplet RP System

5.3.4 Rectangular (21*18) shape

Select rectangular in AlphaCAM from geometry pull down menu, enter (0,0) for the First corner and (21,18) for the second corner.

Some parameters for tool path generation

Tool	Flat 3mm 2F EC HSS
Tool Directions	CCW
Pocketing Type	Linear
Final Depth	-6 mm
Number of Cuts	3
Width of Cut	3 mm

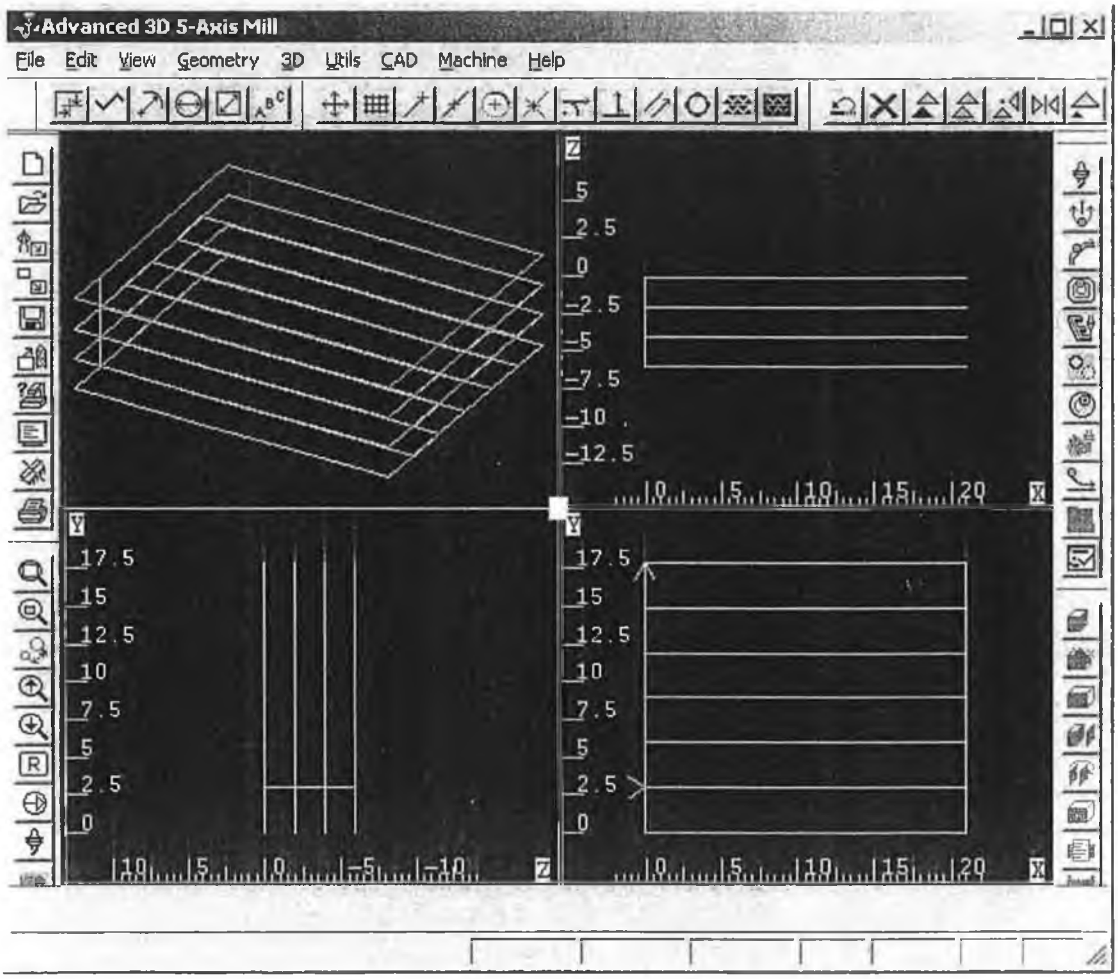


*Figure 92 Tool path generated in AlphaCAM for (21*18) Rectangular shape*

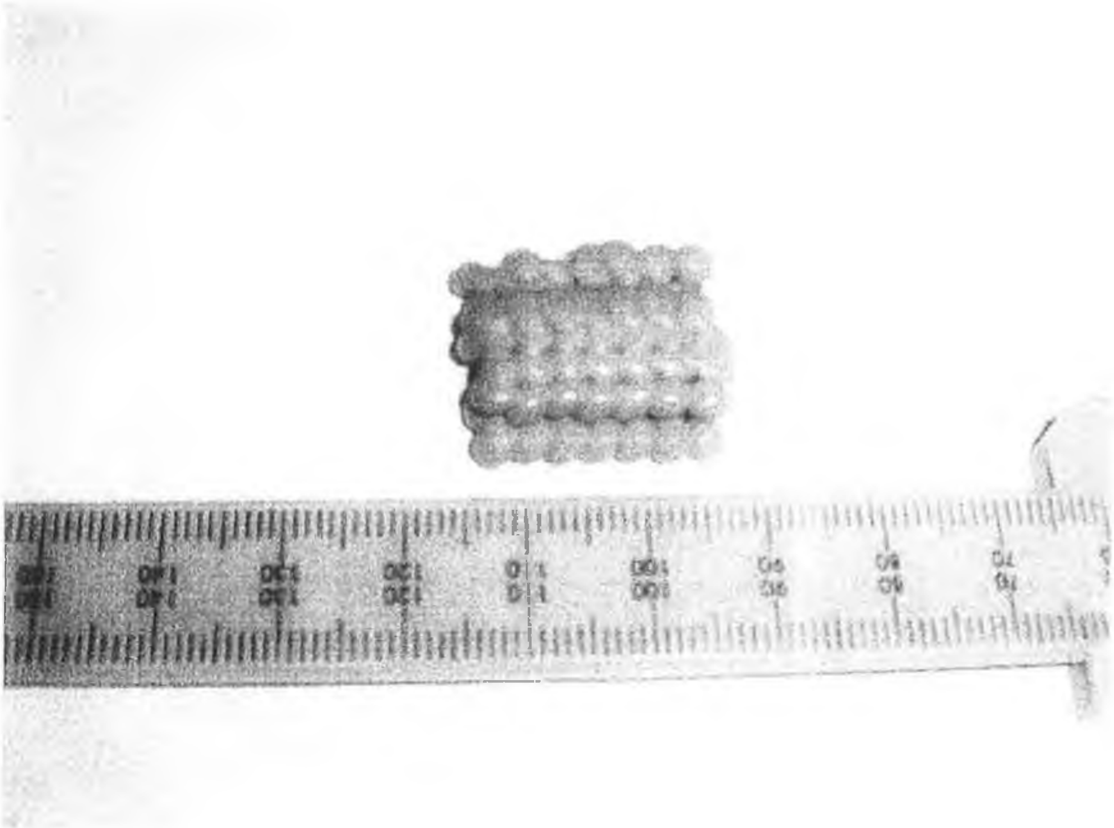


*Figure 93 Rectangular (21*18) shape deposited using Wax Droplet RP System*

5.3.5 Rectangular shape (30*30)

In AlphaCAM Select rectangular from geometry pull down menu, enter (0,0) for the First corner and (30,30) for the second corner.

Some parameters for tool path generation

Tool	Flat 3mm 2F EC HSS
Tool Directions	CW
Pocketing Type	Linear
Final Depth	-6 mm
Number of Cuts	3
Width of Cut	3 mm

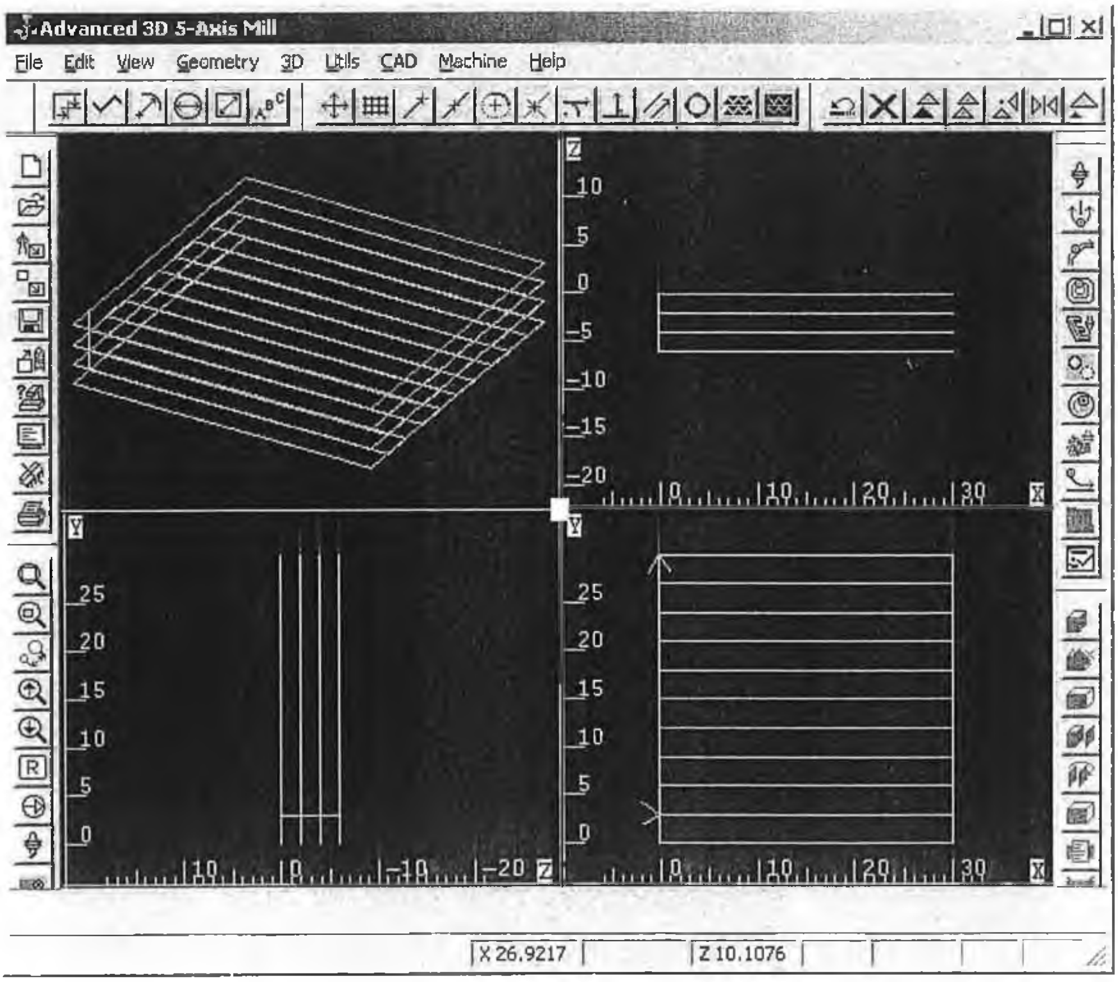


*Figure 94 Tool path generated in AlphaCAM for Rectangular shape (30*30)*

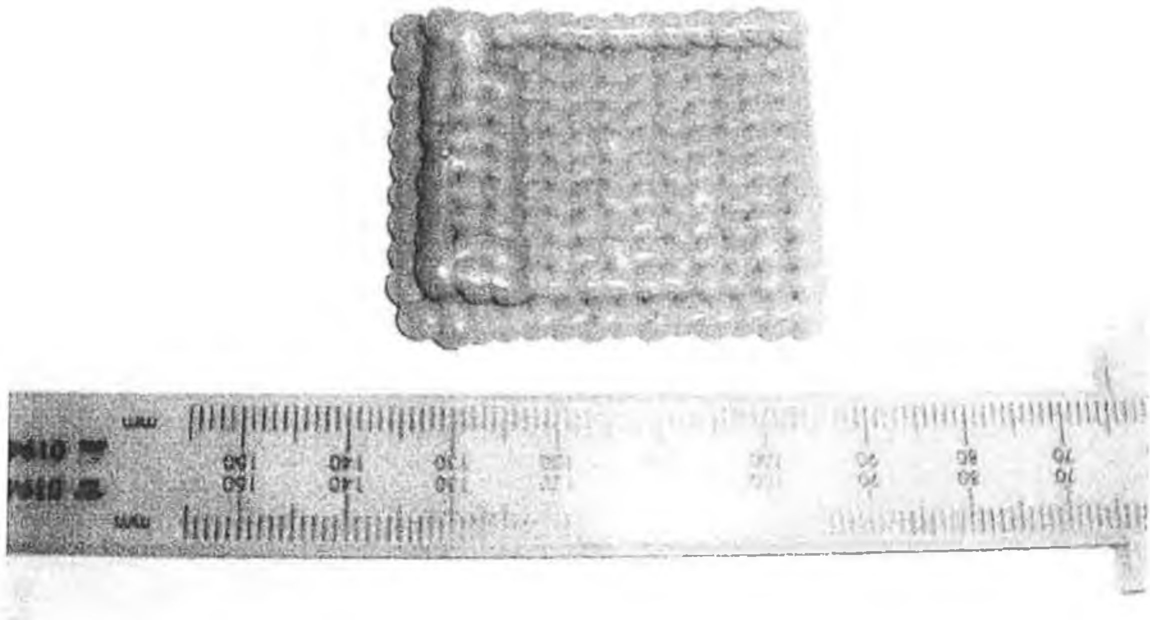


*Figure 95 Rectangular shape (30*30) deposited using Wax Droplet RP System*

Chapter 6 Conclusion and Suggested Future Work

6.1 Advantages of Using CAD/CAM for RP.

Even thought this technique is not fully automated, where the tool path has to be generated in CAD/CAM software for the design, this may causes a delay in the operation, but it has many advantages:

a. Data transfer: many problems related to this issue were discussed in section 1. By directly using CAD/CAM packages the author overcame this problem, and there is no need to transfer CAD data to any other format.

10. Process planning: such as slicing the geometry, tool path generation and building the support structure, are the basic requirements for any RP software. Using this strategy ends the need to develop algorithms to carry out these tasks.

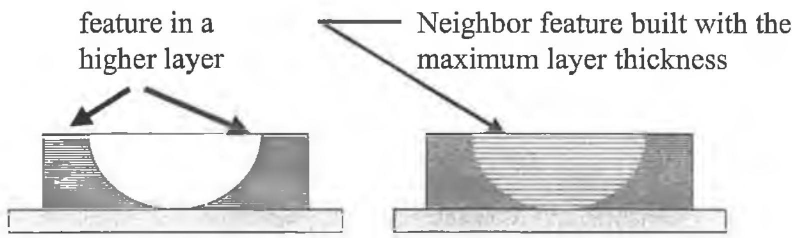
11. Availability of CAD/CAM: another advantage of using this strategy is the availability of CAD/CAM software; the large number of operators and engineers are familiar with using these software and using CNC code. This will expand the use of material addition technology on the horizon.

12. Multi patterns structure: A different filling pattern in the same layer gives a different surface finish and different material property; this technique is possible in this strategy by machining different areas with different patterns.

13. Adaptive Slicing technology: is a new technique used to obtain the surface finish with minimal number of layers see section 2, this technique can be achieved using the suggested strategy.

14. Multiple material fabricate: Although this is a very new technique RP see section 2.6.5, the strategy suggested is capable of performing this task, by selecting different machining tools in CAD/CAM system for each material requested, then use its tool path to drive the selected deposition head, which deposits the specified material.

15. Non-planar layer fabrication: this is another advantage in using this strategy, which is not possible in traditional RP techniques, the capability to build selected features in higher layers. This provides an opportunity to build the neighbour feature with the maximum build layer thickness, which gives a faster build operation see Figure 96. This technique is possible in this strategy, by choosing to build the part with feature sequence instead of layer-by-layer sequence.



(a) feature built in a higher layer (b) feature built with the maximum layer thickness

Figure 96 Non-planar layer fabrication

6.2 Thesis Contribution

In the course of this research, it is believed that the following contributions have been made in the general area of the research topic.

a. Processing STL files: STL is the de-facto standard for the data input for all types of RP systems. The author developed many algorithms to process STL file, slicing algorithm, contour sorting algorithm and contour filling algorithm. The CAD model data can be completely transferred to CAM program for producing the product.

16. Processing CNC code: the author developed translating algorithm for CNC code, which provides the capability to use G code from machining packages such as AlphaCAM and Pro Engineering etc for RP.

17. X language Processor: the author developed an algorithm to build PC23 instruction automatically.

18. Modifying CAM/RP to become user-friendly software to control the Wax Droplet RP System. CAM/RP can be executed by selecting Export from file men

6.3 Suggested Future Work

The wax droplet RP system was designed to deposit the wax as droplets, this system can be enhanced to deposit the wax as bead similar to FDM system, and also it can be combined to build a hybrid system.

Although the new strategy proceeds in different steps as emphasized early, and does not use STL format for data exchange, it is still possible to communicate with the other RP systems.

A different format called Slice format are used as a data exchange format in some systems. After the STL data of the geometry is imported to the system, the slice format is generated for the part. Slice format stores the geometrical information for each layer. This information includes the layer thickness the boundaries of the solid material, the hatches, which define the filling and the support structures. Slice format has been considered as a replacement for STL format [5].

Developing an algorithm to extract the required information for each layer from CNC code then format it into one of the slicing format interfaces such as CLI, LEAF, HP-GL, and SLC format. This information can be feed to any commercial RP machine that uses this format.

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Appendix A Preparatory codes [59]

G code	Function	Modal	Group
G0	Linear Rapid	Yes	01
G1	Linear Feed		
G2	Circular clockwies Feed		
G3	Circular Anti-clockwies Feed		
G4	Dwell	No	00
G7.1	Cylindrical Interpolation	Yes	00
G9	Exact Stop	No	00
G10	Programmable Data	No	00
G11	Programmable Data cancel	No	00
G15	Polar Coordinate cancel	Yes	17
G16	Polar Coordinate		
G17	XY Plane selection	Yes	02
G18	XZ Plane selection		
G19	YZ Plane selection		
G20	Inch units	Yes	06
G21	Metric units		
G27	Reference position return check	No	00
G28	Returen to Reference position		

G29	Returen from Reference position		
G30	2^{nd} ,3^{rd} & 4^{th} Reference position Returen		
G31	Skip Function	No	00
G40	Cutter Compensation Cancel		
G41	Cutter Compensation Left	Yes	07
G42	Cutter Compensation Rigth		
G43	Tool length Compensation+		
G44	Tool length Compensation-	Yes	08
G49	Tool length Compensation cancel		
G50	Scaling Cancel	Yes	11
G51	Scaling Active		
G52	Local coordinate System	Yes	
G53	Machine Coordinate System		
G54	Workpice Coordinate System 1		14
G55	Workpice Coordinate System		
G56	2 Workpice Coordinate System 3		
G57	Workpice Coordinate System 4		

G58	Workpice Coordinate System 5		
G59	Workpice Coordinate System 6		
G61	Exact Stop Mode		
G62	Automatic Corner Feed Over	Yes	15
G63	Tapping Mode		
G64	Cutting Mode	Yes	15
G65	Macro Call	No	00
G66	Custom Macro Call	Yes	
G67	Custom Macro Call cancel		
G68	Coordinate Rotation	Yes	16
G69	Coordinate Rotation cancel		
G90	Absolute command	Yes	03
G91	Incremental command		
G92	Workpice coordinate setting	No	00
G92.1	Workpice coordinate Pre-set		
G94	Feed per minute	Yes	05
G95	Feed per revolution		
G98	Return to hole cycle initial point	Yes	10
G99	Return to hol cycle rlative point	Yes	

Appendix B Command Listing [53]

A	Acceleration
AB	Report analogy, Voltage, binary
AV	Report analogy, Voltage, ASCII
B	Buffer status
CG	Continue
CM	Correction Gain
CR	Carriage return
D	Distance
DB	Dead band
DPA	Display position actual
DW	Set dead band window
ER	Encoder resolution
FR	Encoder function report
FSA	Set incremental/absolute mode
FSB	Set indexer to motor/ Encoder mode
FSC	Position maintenance
FSD	Stop on stall
FSE	Enable output\ 6 on stall
G	Go
GNNN	Synchronized Go
GA	Go home
^H	Backspace
H	Set direction
I	Load move data
IO	Immediate output
IS	Input status
J	Enable/disable joystick
JB	Set joy stick backlash
JD	Set joy sick dead band
JV	Set joy stick backlash compensation velocity
JZ	Set joy stick to zero
K	Kill
L	Loop
LA	Limit acceleration
LD	Limit disable
MA	Mode alternate
MC	Mode continuous
MN	Mode normal

MPA	Mode position absolute
MPI	Mode position incremental
MR	Select motor resolution
MSL	Identify clock source for timed data streaming
MSS	Set maximum correction velocity
MV	End of loop
N	Out put
O	Output
Or	Report Function Setups
Osa	Set Encoder Direction
Osb	Back Up To Home
Osc	Define Active State Of Home Switch
Osd	Define Active State Of Encoder?S Z Channel Input
Ose	Enable Stall Detect
Osf	Set Maximum Joystick Velocity
Osg	Set Final Go Home Direction
Osh	Reference Edge Of Home Switch
P (	Report Incremental Position, Ascii
PB	Report Incremental Position, Binary
Pr	Report Absolute Position
Ps	Pause
Px	Report Encoder Absolute Position Ascii
Pxb	Report Encoder Absolute Position .Binary
PX	Position Zero
PXB	Report Encoder Absolute Position,Binary
PZ	Position Zero
Q	Complete Current Command And Clear Command Buffer
Q	Ø(Exit Streaming Mode
Q1	Enter Immediate Velocity Streaming Mode
Q2	Enter Time ?Distance Streaming Mode
Q3	Enter Time-Velocity Streaming Mode
QI	Report Status Of Qs Command
QIB	Interrupt Status Report , Binary
QR	Report Qs Command Function Enable Status
QS	Interrupt On Signal Commands
QSA	Interrupt On Trigger #1 High
QSB	Interrupt On Move Complete
QSD	Interrupt Signal On Limit Encountered
QSE	(Interrupt On Ready To Respond)
QSG	(Interrupt On Command Buffer Full)
QSH	(Interrupt On Motor Stall)

R	(Request Indexer Status)
RA	(Limit Switch Status Report)
RB	(Report Loop,Pause, Shutdown,Trigger Status)
RC	(Report Closed Loop And Go Home Status)
RM	(Rate Multiplier In Immediate Velocity Streaming Mode)
RV	(Report Software Part Number)
S	(Stop)
SA	(Stop All)
SD	(Define Timed Data Streaming Mode Streaming Data)
SR	(Report Configuration Status)
SSD	(Mode Alternate Stop Mode)
SSF	(Normal/Low Velocity Range)
SSG	(Clear/Save The Command Buffer On Limit)
SSH	(Clear/Save The Command Buffer On Stop)
ST	(Shutdown)
T	(Time Delay)
TD	(Set Time Interval For Timed Data Streaming Mode)
TR	(Wait For Trigger)
TS	(Report Trigger Status)
U	(Pause And Wait For Continue)
UR	(Report Scale Factor Status)
US	(Set Position Scale Factor)
V	(Velocity)
W1	(Signed Binary Position Report)
W3	(Hexadecimal Position Report)
Y	(Stop Loop)

Appendix C CAD/RP

Appendix C 1: X-Y menu algorithm

```
Picture1.Cls
Open "C:\triangles.txt" For Input As #1
Open "C:\Drawing.txt" For Output As #2
Do Until EOF(1)
Input #1, xa, ya, za, xb, yb, zb, xc, yc, zc
Write #2, xa, ya, xb, yb
Write #2, xa, ya, xc, yc
Write #2, xc, yc, xb, yb
Loop
Close #1
Close #2
mnuzoom_Click
```

Appendix C 2: 3D menu

```
Open "C:\triangles.txt" For Input As #1
Open "C:\Drawing.txt" For Output As #2
Picture1.Cls
Do Until EOF(1)
Input #1, xa, ya, za, xb, yb, zb, xc, yc, zc
la = Sqr(xa ^ 2 + ya ^ 2)
ta = atan2(xa, ya)
xa = la * Cos((30 + ta) * 3.14 / 180)
ya = za + la * Sin(30 * 4.14 / 180)
lb = Sqr(xb ^ 2 + yb ^ 2)
tb = atan2(xb, yb)
xb = lb * Cos((30 + tb) * 3.14 / 180)
yb = zb + lb * Sin(30 * 4.14 / 180)
Lc = Sqr(xc ^ 2 + yc ^ 2)
tc = atan2(xc, yc)
xc = Lc * Cos((30 + tc) * 3.14 / 180)
yc = zc + Lc * Sin(30 * 4.14 / 180)
Write #2, xa, ya, xb, yb
Write #2, xa, ya, xc, yc
Write #2, xc, yc, xb, yb
```

```
Loop
Close #1
Close #2
mnuzoom_Click
```

Appendix C3: Slicing algorithm

```
'*********************************************************************'
                    starting slicing with layer thickness of d
'*********************************************************************

Public Sub SliceSTL()
outfile1 = "c:\slidesSTL.TXT"
n = 0
Call Picture1.Cls
Open outfile1 For Output As #2
Open infile For Input As #1
Do Until EOF(1)
  Input #1, Target
  If Target = "outer loop" Then
 Input #1, Target1
  Vertex (Target1)
  x1 = Val(Vertex_x)
  y1 = Val(Vertex_y)
  z1 = Val(Vertex_z)
 Input #1, Target2
  Vertex (Target2)
  x2 = Val(Vertex_x)
  y2 = Val(Vertex_y)
  z2 = Val(Vertex_z)
 Input #1, Target3
  Vertex (Target3)
  x3 = Val(Vertex_x)
  y3 = Val(Vertex_y)
  z3 = Val(Vertex_z)
'*********************************************************************
          ' check which line intersect with the plane & find the intersection points
'*********************************************************************
  If z = z1 And z = z2 And z = z3 Then
  ignor = 1
```

```
ElseIf z = z1 And z = z2 And z3 > z Then  ' Groub 4 Case a
Write #2, x1, y1, x2, y2
Picture1.Line (x1, y1)-(x2, y2)
Call slow
DoEvents
n = n + 1
ElseIf z = z1 And z = z3 And z2 > z Then     ' Groub 4 Case b
Write #2, x1, y1, x3, y3
Picture1.Line (x1, y1)-(x3, y3)
Call slow
DoEvents
n = n + 1
ElseIf z = z2 And z = z3 And z1 > z Then     ' Groub 4 Case c
Write #2, x2, y2, x3, y3
Picture1.Line (x2, y2)-(x3, y3)
Call slow
DoEvents
n = n + 1

ElseIf z = z1 And ((z > z2 And z < z3) Or (z < z2 And z > z3)) Then 'Groub 2 Case a
  x23 = x2 + (z - z2) * (x3 - x2) / (z3 - z2)
  y23 = y2 + (z - z2) * (y3 - y2) / (z3 - z2)
  Write #2, x1, y1, x23, y23
  Picture1.Line (x1, y1)-(x23, y23)
  Call slow
  DoEvents
  n = n + 1
ElseIf z = z2 And ((z > z1 And z < z3) Or (z < z1 And z > z3)) Then 'Groub 2 Case b
  x13 = x1 + (z - z1) * (x3 - x1) / (z3 - z1)
  y13 = y1 + (z - z1) * (y3 - y1) / (z3 - z1)
  Write #2, x2, y2, x13, y13
  Picture1.Line (x2, y2)-(x13, y13)
  Call slow
  DoEvents
  n = n + 1

ElseIf z = z3 And ((z > z1 And z < z2) Or (z < z1 And z > z2)) Then 'Groub 2 Case c
  x12 = x1 + (z - z1) * (x2 - x1) / (z2 - z1)
  y12 = y1 + (z - z1) * (y2 - y1) / (z2 - z1)
  Write #2, x3, y3, x12, y12
```

```
 Picture1.Line (x3, y3)-(x12, y12)
 Call slow
 DoEvents
 n = n + 1

ElseIf (z > z1 And z < z2) Or (z < z1 And z > z2) Then
x12 = x1 + (z - z1) * (x2 - x1) / (z2 - z1)
y12 = y1 + (z - z1) * (y2 - y1) / (z2 - z1)
  If (z > z1 And z < z3) Or (z < z1 And z > z3) Then    'Group1 case A
  x13 = x1 + (z - z1) * (x3 - x1) / (z3 - z1)
  y13 = y1 + (z - z1) * (y3 - y1) / (z3 - z1)
  Write #2, x12, y12, x13, y13
   Picture1.Line (x12, y12)-(x13, y13)
  Call slow
  DoEvents
  n = n + 1

  ElseIf (z > z2 And z < z3) Or (z < z2 And z > z3) Then   'Group1 case B
  x23 = x2 + (z - z2) * (x3 - x2) / (z3 - z2)
  y23 = y2 + (z - z2) * (y3 - y2) / (z3 - z2)
  Write #2, x12, y12, x23, y23
   Picture1.Line (x12, y12)-(x23, y23)
  Call slow
  DoEvents
  n = n + 1
  End If

ElseIf (z > z3 And z < z2) Or (z < z3 And z > z2) Then  ' Group1 Case C
  x23 = x2 + (z - z2) * (x3 - x2) / (z3 - z2)
  y23 = y2 + (z - z2) * (y3 - y2) / (z3 - z2)

  If (z > z1 And z < z3) Or (z < z1 And z > z3) Then
  x13 = x1 + (z - z1) * (x3 - x1) / (z3 - z1)
  y13 = y1 + (z - z1) * (y3 - y1) / (z3 - z1)
  Write #2, x23, y23, x13, y13
   Picture1.Line (x23, y23)-(x13, y13)
  Call slow
  DoEvents
  n = n + 1
  End If
```

```
  End If

End If

Loop
Close #1
Close #2
End Sub
```

Appendix C4 Contour Construction algorithm

```
Public Sub contour_ordering()
coun_con = 0
Call Picture1.Cls
outfile2 = "c:\countor_in _order.TXT"
Open outfile1 For Input As #1
Input #1, xa1, ya1, xb1, yb1
Close #1
Open outfile2 For Output As #2
Write #2, xa1, ya1, xb1, yb1, z
Close #2
Write #6, xa1, ya1, xb1, yb1, z
coun_con = coun_con + 1
Picture1.Line (xa1, ya1)-(xb1, yb1), vbRed
For q = 1 To n
  If q <> 1 Then
        Open outfile1 For Input As #1
        For h = 1 To n          'to pick new line from new contour
        Input #1, xa1, ya1, xb1, yb1
        rep = 0
        Open outfile2 For Input As #2   'check if this contour does exist in the new list
           Do Until EOF(2)
           Input #2, a, b, c, e, f
           If (xa1 = a And ya1 = b And xb1 = c And yb1 = e) Or (xa1 = c And ya1 = e
And xb1 = a And yb1 = b) Then
           rep = rep + 1
           End If
           Loop
        Close #2
```

```
            If rep = 0 Then
            Exit For
            End If
          Next h
          Close #1
      Open outfile2 For Append As #2                              'add this line to new list
      Write #2, xa1, ya1, xb1, yb1, z
      Close #2
      Write #6, xa1, ya1, xb1, yb1, z
      coun_con = coun_con + 1
      Picture1.Line (xa1, ya1)-(xb1, yb1), vbRed
      End If
    xa = xa1
    ya = ya1
    Do Until xa = xb And ya = yb    ' search to close the contour
    Open outfile1 For Input As #1
    For k = 1 To n
    Input #1, xa2, ya2, xb2, yb2
    If xb1 = xa2 And yb1 = ya2 And (xa1 <> xb2 Or ya1 <> yb2) Then
    Open outfile2 For Append As #2
    Write #2, xa2, ya2, xb2, yb2, z
    Close #2
    Write #6, xa2, ya2, xb2, yb2, z
    Picture1.Line (xa2, ya2)-(xb2, yb2), vbRed
    xa1 = xa2
    ya1 = ya2
    xb1 = xb2
    yb1 = yb2
    xb = xb2
    yb = yb2
    coun_con = coun_con + 1
    ElseIf xb1 = xb2 And yb1 = yb2 And (xa1 <> xa2 Or ya1 <> ya2) Then
    Open outfile2 For Append As #2
    Write #2, xb2, yb2, xa2, ya2, z
    Close #2
    Write #6, xb2, yb2, xa2, ya2, z
    Picture1.Line (xb2, yb2)-(xa2, ya2), vbRed
    xa1 = xb2
    ya1 = yb2
    xb1 = xa2
```

```
yb1 = ya2
xb = xa2
yb = ya2
coun_con = coun_con + 1
End If
DoEvents
Next k
Close #1
DoEvents
Loop
Call slow
If coun_con >= n Then
Exit For
End If
Next q
Close #1
Close #2
End Sub
```

Appendix C5 Filling the pattern algorithm

```
Public Sub Fill_patren()

'*****************************************************************
'                    finde intersection with y
'*****************************************************************

outfile4 = "c:\jghdfoiu.txt"
Open outfile4 For Output As #15



m = 0
For y = (ymin + dyf) To (ymax - dyf) Step dyf

Open outfile1 For Input As #4
p = 0   'number of intersection

    For k = 1 To n

        Input #4, xa, ya, xb, yb
```

```
        If (y >= ya And y < yb) Or (y >= yb And y < ya) Then
        p = p + 1
        x(p) = (y - ya) * (xb - xa) / (yb - ya) + xa
        End If

    Next

Close #4

    If p > 0 Then
    m = m + p
    For h = 1 To p
      Write #15, x(h), y, p
    Next h
    End If
DoEvents
Next
Close #15

'*******************************************************************************
        ' find the pointes in the same livel and joine 1 to 2 and 3 to 4
'*******************************************************************************

infile4 = outfile4
Call slow
Open infile4 For Input As #7
k = 1
p = 1
v = 1
w = 1
n_o_i = 0
  For k = 1 To m
'**********************************
'order the points in ths same level
'**********************************
n_o_i = n_o_i + 1

  r = 1
  Input #7, xa, ya, p
  x(r) = xa
```

```
  For r = 2 To p
    Input #7, xa, ya, p
    x(r) = xa
  Next r


  For v = 1 To (p - 1)
    If x(v + 1) < x(v) Then
    a = x(v)
    x(v) = x(v + 1)
    x(v + 1) = a

      If v >= 2 Then
      w = 1
      For w = v To 1 Step -1
      If x(w) < x(w - 1) Then
        b = x(w - 1)
        x(w - 1) = x(w)
        x(w) = b
        Else
        Exit For
        End If
      Next w
      End If
    End If
  Next v

If (-1) ^ n_o_i < 0 Then

  For l = 1 To p Step 2

   Picture1.Line (x(l), ya)-(x(l + 1), ya), vbRed
  Write #6, x(l), ya, x(l + 1), ya, z

   Call slow
   DoEvents

   Next l
Else
  For l = (p - 1) To 1 Step -2
```

```
 Picture1.Line (x(l + 1), ya)-(x(l), ya), vbRed
  Write #6, x(l + 1), ya, x(l), ya, z

   Call slow
   DoEvents

   Next l
End If

k = k + p - 1
DoEvents

Next k
Close #7



End Sub
```

Appendix C6 Simulate the deposition algorithm

```
Public Sub simulat()
x1 = 0
y1 = 0
z1 = 0
D_drop = 3
LD = 3

Open outfile5 For Input As #1

Do Until EOF(1)

Input #1, xa, ya, xb, yb, z1


Dx = xb - xa
dy = yb - ya
Dt = (Dx ^ 2 + dy ^ 2) ^ (1 / 2)


If Abs(Dt) >= LD Then
```

```
  mn = Dt / LD                    'number of motion
  wx = xa
  wy = ya
  For k = 1 To mn
    If Dx = 0 And dy <> 0 Then
     wy = wy + LD * dy / Dt
    ElseIf Dx <> 0 And dy = 0 Then
     wx = wx + LD * Dx / Dt
    ElseIf dy <> 0 And Dx <> 0 Then
    wx = wx + LD * Dx / Dt
    wy = wy + LD * dy / Dt
    End If
    Picture1.Circle (wx, wy), D_drop / 2 ', Deposition_color
    Call slow
    DoEvents

    Write #5, wx, wy, z1

    Call slow

  Next k

End If


Loop

Close #1

End Sub
```

Appendix C7 Build the instruction file

```
Public Sub Build()
x1 = 0
y1 = 0

List1.Clear
List1.Visible = True
```

```
Input #1, G, xco, yco, zco, i, j, r
a = Mid$(xco, 1, 1)
b = Mid$(yco, 1, 1)
c = Mid$(zco, 1, 1)
Ei = Mid$(i, 1, 1)

Fj = Mid$(j, 1, 1)
Gr = Mid$(r, 1, 1)
If IsNumeric(a) Or IsNumeric(b) Or IsNumeric(c) Or c = "-" Then
If IsNumeric(a) Or a = "-" Then
x_n = Val(xco) ' numirc values for x only
End If
If IsNumeric(b) Or b = "-" Then
y_n = Val(yco)
End If
If IsNumeric(c) Or c = "-" Then
z_n = Val(zco)
If z_n < 0 Then
z_n = Lv - z_n ' value of Z >0
End If
End If
If IsNumeric(Ei) Then
I_N = Val(i)
Else
I_N = 0
End If
If IsNumeric(Fj) Then
J_N = Val(j)
Else
J_N = 0
End If
If IsNumeric(Gr) Then
r_N = Val(r)
Else
r_N = 0
End If

Write #2, G, x_n, y_n, z_n, I_N, J_N, r_N
ts = ts + 1
End If
```

```
    End If
    Vx = Format$(Vx, "0.0000")
    Vy = Format$(Vy, "0.0000")
    First_part = " LD3" & Position_modes & Mode_moves & xaxis_motor & "V" &
Vx & xaxis_motor & "D" & Dxp
     second_part = yaxis_motor & "V" & Vy & yaxis_motor & "D" & Dyp & " G12
P "
   End If
result = First_part & second_part
Write #2, result
Write #2, message1
Write #2, message2
List1.AddItem result
List1.AddItem message1
List1.AddItem message2
x1 = x2
y1 = y2
Loop
Close #2
Close #1
End Sub
```

Appendix D CNC/RP

Appendix D 1 Extract the tool path

```
Public Sub Extract_data()
List1.Visible = False

xmin = 0
xmax = 0
ymin = 0
ymax = 0
xa = 0
xb = 0
ya = 0
yb = 0
dep_num = 0
Call Picture1.Cls


'*****************************************************************
             'splitting the CNC code into sub program and the main program
'*****************************************************************
Open "c:\main_cnc_program.txt" For Output As #12
Open "c:\sub_cnc_program.txt" For Output As #13
On Error GoTo HandleErrors

Open infile For Input As #1

Do
   Input #1, Target1
   If InStr(Target1, "N20") > 0 Then
  Exit Do
  End If
Loop

Do Until target2 = "%"
  Input #1, target2
  If InStr(target2, ":1") > 0 Then
    Do Until target3 = "%"
     Input #1, target3
```

```
    Write #13, target3
   Loop

  Exit Do
  End If

  Write #12, target2
Loop


Close #1
Close #12
Close #13

'*************************************************************************
                         'extract the stringes after G,x,y,z
'*************************************************************************
outfile1 = "c:\Useful_cnc_data.txt"
Open "c:\main_cnc_program.txt" For Input As #12
Open "c:\sub_cnc_program.txt" For Input As #13

Open outfile1 For Output As #2



Do Until EOF(12)
  xco = ""
  yco = ""
  zco = ""
  i = ""
  j = ""
  r = ""

  Input #12, targetstra


        If InStr(targetstra, "G0") > 0 Then
        G = 0
        ElseIf InStr(targetstra, "G1") > 0 Then
        G = 1
        ElseIf InStr(targetstra, "G2") > 0 Then
```

```
G = 2

ElseIf InStr(targetstra, "G3") > 0 Then
G = 3
Else
G = G
End If

If InStr(targetstra, "X") > 0 Then
startpositionx = InStr(targetstra, "X") + 1
xco = Mid$(targetstra, startpositionx, 6)
End If


If InStr(targetstra, "Y") > 0 Then
startpositiony = InStr(targetstra, "Y") + 1
yco = Mid$(targetstra, startpositiony, 6)
End If


If InStr(targetstra, "Z") > 0 Then
startpositionz = InStr(targetstra, "Z") + 1
zco = Mid$(targetstra, startpositionz, 3)
End If

If InStr(targetstra, "I") > 0 Then
startpositionx = InStr(targetstra, "I") + 1
i = Mid$(targetstra, startpositionx, 6)
End If


If InStr(targetstra, "J") > 0 Then
startpositiony = InStr(targetstra, "K") + 1
j = Mid$(targetstra, startpositiony, 6)
End If

If InStr(targetstra, "R") > 0 Then
startpositiony = InStr(targetstra, "R") + 1
r = Mid$(targetstra, startpositiony, 6)
End If
```

```
If InStr(targetstra, "M98") > 0 Then
Do Until EOF(13)
     t = t + 1
    xco = ""
    yco = ""
    zco = ""
    i = ""
    j = ""
    r = ""

     Input #13, targetstrb

    If InStr(targetstrb, "G0") > 0 Then
    G = 0
    ElseIf InStr(targetstrb, "G1") > 0 Then
    G = 1
    ElseIf InStr(targetstrb, "G2") > 0 Then
    G = 2
    ElseIf InStr(targetstrb, "G3") > 0 Then
    G = 3
    Else
    G = G
    End If

    If InStr(targetstrb, "X") > 0 Then
    startpositionx = InStr(targetstrb, "X") + 1
    xco = Mid$(targetstrb, startpositionx, 6)
    End If


    If InStr(targetstrb, "Y") > 0 Then
    startpositiony = InStr(targetstrb, "Y") + 1
    yco = Mid$(targetstrb, startpositiony, 6)
    End If


    If InStr(targetstrb, "Z") > 0 Then
    startpositionz = InStr(targetstrb, "Z") + 1
    xco = Mid$(targetstrb, startpositionz, 3)
    End If
```

```
        If InStr(targetstrb, "I") > 0 Then

        startpositionx = InStr(targetstrb, "I") + 1

        i = Mid$(targetstrb, startpositionx, 6)
        End If


        If InStr(targetstrb, "J") > 0 Then
        startpositiony = InStr(targetstrb, "J") + 1
        j = Mid$(targetstrb, startpositiony, 6)
        End If

        If InStr(targetstrb, "R") > 0 Then
        startpositiony = InStr(targetstrb, "R") + 1
        r = Mid$(targetstrb, startpositiony, 6)
        End If


        Write #2, G, xco, yco, zco, i, j, r

    Loop

    End If

  Write #2, G, xco, yco, zco, i, j, r

Loop

Close #2
Close #12
Close #13
'*****************************************************************************'
                          check if the strings are numeric
'*****************************************************************************
Open outfile1 For Input As #1
outfile2 = "c:\Numerical_CNC_Data.txt"
Open outfile2 For Output As #2

  Do Until EOF(1)
```

```
Input #1, G, xco, yco, zco, i, j, r
a = Mid$(xco, 1, 1)
b = Mid$(yco, 1, 1)
c = Mid$(zco, 1, 1)
Ei = Mid$(i, 1, 1)

Fj = Mid$(j, 1, 1)
Gr = Mid$(r, 1, 1)
If IsNumeric(a) Or IsNumeric(b) Or IsNumeric(c) Or c = "-" Then
If IsNumeric(a) Or a = "-" Then
x_n = Val(xco) ' numirc values for x only
End If
If IsNumeric(b) Or b = "-" Then
y_n = Val(yco)
End If
If IsNumeric(c) Or c = "-" Then
z_n = Val(zco)
If z_n < 0 Then
z_n = Lv - z_n ' value of Z >0
End If
End If
If IsNumeric(Ei) Then
I_N = Val(i)
Else
I_N = 0
End If
If IsNumeric(Fj) Then
J_N = Val(j)
Else
J_N = 0
End If
If IsNumeric(Gr) Then
r_N = Val(r)
Else
r_N = 0
End If

Write #2, G, x_n, y_n, z_n, I_N, J_N, r_N
ts = ts + 1
End If
```

```
Loop

Close #1
Close #2

'**********************************************************************
                    ' Sorting the circular enterpolation
'**********************************************************************

outfile3 = "c:\Sorting_Data_linear.txt"
  Open outfile2 For Input As #1
  Open outfile3 For Output As #2
   n = 0

 Do Until EOF(1)
  Input #1, G, x2, y2, z2, i, j, r


'****************************************Find xmax & xmin
      If x2 < xmin Then
      xmin = x2
      End If
      If x2 > xmax Then
      xmax = x2
      End If

      '************************** Find ymax & ymin
      If y2 < ymin Then
      ymin = y2
      End If
      If y2 > ymax Then
      ymax = y2
      End If

      '**************************Find max
      If xmax > ymax Then
      max_s = xmax
      Else
      max_s = ymax
```

```
End If

'**************************Find min
If xmin < ymin Then
min_s = xmin
Else

min_s = ymin
End If

'*************************************


If G = 2 And i <> 0 And j <> 0 Then
    r = Sqr(i ^ 2 + j ^ 2)
    xc = x1 + i
    yc = y1 + j
    b1 = atan2(i, j)
    I2 = x2 - xc
    J2 = y2 - yc
    b2 = atan2(I2, J2)

    If Lc > r Then
    Lc = r
    End If

    Step = Lc * 180 / (r * (4 * Atn(1)))
    For b = b1 To b2 Step -Step
        If b = 0 Then
        b = 360
        End If
    xco = xc + (r * Cos(b * (4 * Atn(1)) / 180))
    yco = yc + (r * Sin(b * (4 * Atn(1)) / 180))
    n = n + 1

    Write #2, G, xco, yco, zco
    x2 = xco
    y2 = yco
    x1 = x2
    y1 = y2
```

```
        Next

    End If

    If G = 3 And i <> 0 And j <> 0 Then
        xc = x1 + i
        yc = y1 + j
          b1 = atan2(i, j)

         I2 = x2 - xc
         J2 = y2 - yc
         b2 = atan2(I2, J2)

         If Lc > r Then
         Lc = r
         End If

        Step = Lc * 180 / (r * (4 * Atn(1)))
        For b = b1 To b2 Step Step
           If b = 360 Then
           b = 0
           End If

        xco = xc + (r * Cos(b * (4 * Atn(1)) / 180))
        yco = yc + (r * Sin(b * (4 * Atn(1)) / 180))
        n = n + 1
        Write #2, G, xco, yco, zco
         x2 = xco
         y2 = yco
         x1 = x2
         y1 = y2
       Next

    End If
```

Appendix D 2 atan2 function

```
Public Function atan2(X, Y)
Pi = 4 * Atn(1)
If X > 0 And Y > 0 Then
```

```
atan2 = Atn(Y / X)
ElseIf X > 0 And Y < 0 Then
atan2 = 2 * Pi + Atn(Y / X)
ElseIf X < 0 And Y > 0 Then
atan2 = Pi - Atn(Abs(Y / X))
ElseIf X < 0 And Y < 0 Then
atan2 = Atn(Abs(Y / X)) + Pi
ElseIf X = 0 And Y > 0 Then
atan2 = Pi / 2
ElseIf X = 0 And Y < 0 Then
atan2 = 3 / 2 * Pi
ElseIf Y = 0 And X > 0 Then
atan2 = 0
ElseIf Y = 0 And X < 0 Then
atan2 = Pi
ElseIf X = 0 And Y = 0 Then
atan2 = 0
End If
atan2 = 180 * atan2 / Pi
End Function
```

Appendix D 3 Decipher the circular interpolation

```
If r <> 0 And (G = 2 Or G = 3) Then ' find the center of the arc
        r = Val(r)

Step = Lc * 180 / (r * (4 * Atn(1)))
xm = (x1 + x2) / 2
ym = (y1 + y2) / 2
y12 = (y1 - y2) / 2
x12 = (x1 - x2) / 2


xca = xm + y12 * Sqr((r ^ 2 / (x12 ^ 2 + y12 ^ 2)) - 1)
        yca = ym - x12 * Sqr((r ^ 2 / (x12 ^ 2 + y12 ^ 2)) - 1)
        xcb = xm - y12 * Sqr((r ^ 2 / (x12 ^ 2 + y12 ^ 2)) - 1)
        ycb = ym + x12 * Sqr((r ^ 2 / (x12 ^ 2 + y12 ^ 2)) - 1)


dx1a = x1 - xca
```

```
dy1a = y1 - yca
Ga1 = atan2(dx1a, dy1a)

dx2a = x2 - xca
dy2a = y2 - yca
Ga2 = atan2(dx2a, dy2a)

dx1b = x1 - xcb
dy1b = y1 - ycb
Gb1 = atan2(dx1b, dy1b)

dx2b = x2 - xcb
dy2b = y2 - ycb
Gb2 = atan2(dx2b, dy2b)

If G = 3 Then

DGa = Ga2 - Ga1
DGb = Gb2 - Gb1
    If DGa < 0 Then
    Ga2 = Ga2 + 360
    DGa = Ga2 - Ga1
    End If
    If DGb < 0 Then
    Gb2 = Gb2 + 360
    DGb = Gb2 - Gb1
    End If

    If (Abs(DGa) > 180 And Ri = "-") Or (Abs(DGa) <= 180 And Ri <> "-") Then
    For Ga = Ga1 To Ga2 Step Step
    X = xca + (r * Cos(Ga * Pi / 180))
    Y = yca + (r * Sin(Ga * Pi / 180))
    Write #2, G, X, Y, z2
    n = n + 1
    Next Ga
    ElseIf (Abs(DGb) > 180 And Ri = "-") Or (Abs(DGb) <= 180 And Ri <> "-")
Then
    For Gb = Gb1 To Gb2 Step Step
    X = xcb + (r * Cos(Gb * Pi / 180))
    Y = ycb + (r * Sin(Gb * Pi / 180))
```

```
        Write #2, G, X, Y, z2
        n = n + 1
        Next Gb
        End If

ElseIf G = 2 Then

DGa = Ga2 - Ga1
DGb = Gb2 - Gb1
        If DGa > 0 Then
        Ga2 = Ga2 - 360
        DGa = Ga1 - Ga2
        End If
        If DGb > 0 Then
        Gb2 = Gb2 - 360
        DGb = Gb1 - Gb2
        End If

        If (Abs(DGa) > 180 And Ri = "-") Or (Abs(DGa) <= 180 And Ri <> "-") Then
        For Ga = Ga1 To Ga2 Step -Step
        r = Sqr((xca - x1) ^ 2 + (yca - y1) ^ 2)
        X = xca + (r * Cos(Ga * Pi / 180))
        Y = yca + (r * Sin(Ga * Pi / 180))
        Write #2, G, X, Y, z2
        n = n + 1
        Next Ga
        ElseIf (Abs(DGb) > 180 And Ri = "-") Or (Abs(DGb) <= 180 And Ri <> "-")
Then
        For Gb = Gb1 To Gb2 Step -Step
        X = xcb + (r * Cos(Gb * Pi / 180))
        Y = ycb + (r * Sin(Gb * Pi / 180))
        Write #2, G, X, Y, z2
        n = n + 1
        Next Gb

        End If
End If


End If
```

```
    x1 = x2
    y1 = y2
    n = n + 1

 Write #2, G, x2, y2, z2

Loop

Close #1
Close #2
```

Appendix D4 Drawing CNC tool path

```
Public Sub Drawing_CNC()

Call Drawaxis

x1 = 0
y1 = 0
z1 = 0

Open outfile3 For Input As #1

Do Until EOF(1)

    Input #1, G, x2, y2, z2
    If z <> z2 And G <> 0 Then
    Call Picture1.Cls
    Call Drawaxis
    End If
    DoEvents

    Call slow

    If G = 0 Then
    Picture1.Line (x1, y1)-(x2, y2), Filtring_color
    Else
    Picture1.Line (x1, y1)-(x2, y2), Deposition_color
    End If
```

```
        x1 = x2

        y1 = y2
        If z2 <> 0 Then
        z = z2
        End If

Loop

Close #1

End Sub
```

Appendix D4 simulate the deposition of wax

```
Public Sub simulate()

Call Drawaxis

Open outfile3 For Input As #1
Open "c:\positions_for_filtring.txt" For Output As #4  'positions_for filtring
Open "c:\deposition_positions.txt" For Output As #5  'deposition_positions

Input #1, G, wx, wy, z2
z = z2
      Picture1.FillStyle = FillStyle_Dep
      Picture1.FillColor = Deposition_color
      Picture1.Circle (wx, wy), D_drop / 2, Deposition_color
      Write #4, wx, wy, z2
      Write #5, wx, wy, z2

Do Until EOF(1)

Input #1, G, x2, y2, z2

        If z <> z2 And G <> 0 Then
        Call Picture1.Cls
        Call Drawaxis
        End If
        DoEvents
*****************************
```

```
Dx = x2 - wx

Dy = y2 - wy
dt = (Dx ^ 2 + Dy ^ 2) ^ (1 / 2)

'****************************************
If Abs(dt) >= LD And G <> 0 Then
  mn = dt / LD                    'number of motion

  For k = 1 To mn
    If Dx = 0 And Dy <> 0 Then
     wy = wy + LD * Dy / dt
    ElseIf Dx <> 0 And Dy = 0 Then
     wx = wx + LD * Dx / dt
    ElseIf Dy <> 0 And Dx <> 0 Then
    wx = wx + LD * Dx / dt
    wy = wy + LD * Dy / dt
    End If
    Picture1.Circle (wx, wy), D_drop / 2, Deposition_color
    Write #4, wx, wy, z2
    Write #5, wx, wy, z2

    dep_num = dep_num + 1
    Call slow

  Next k

ElseIf G = 0 And Abs(dt) <> 0 Then
   Picture1.Line (wx, wy)-(x2, y2), Filtring_color
   wx = x2
   wy = y2
End If
'***********************
If G <> 0 Then
z = z2
End If

Loop

Close #1
Close #4
```

```
Close #5

End Sub
```

Appendix D5 Correct

```
Private Sub Correct_Click()
outfile5 = "c:\positions_for_filtring.txt"
On Error GoTo HandleErrors
HandleErrors:

If Err.Number = 75 Then
intResponse = MsgBox("file not found", vbOKOnly, "Invalid Path")
Exit Sub
End If

List1.Visible = False
dep_num = 0

Call Picture1.Cls
Call Drawaxis

Open outfile5 For Output As #4                    'positions_for filtring
Open "c:\deposition_positions.txt" For Output As #5    'deposition_positions
Open outfile3 For Input As #1

Input #1, G, x1, y1, z1
z = z1

Do Until EOF(1)

Input #1, G, x2, y2, z2

    If z <> z2 And G <> 0 Then
    Call Picture1.Cls
    Call Drawaxis
    End If
    DoEvents
```

```
Dx = x2 - x1

Dy = y2 - y1
dt = (Dx ^ 2 + Dy ^ 2) ^ (1 / 2)


If Abs(dt) >= LD And G <> 0 Then
mn = dt / LD     'number of steps for this motion
wx = x1          ' starting from the last origenal position in x
wy = y1          ' starting from the last origenal position in y

    Picture1.FillStyle = FillStyle_Dep
    Picture1.FillColor = Deposition_color
    Picture1.Circle (wx, wy), D_drop / 2, Deposition_color
    Write #4, wx, wy, z2
    Write #5, wx, wy, z2
    dep_num = dep_num + 1
    Call slow


  For k = 1 To mn
    If Dx = 0 And Dy <> 0 Then
    wy = wy + LD * Dy / dt
    ElseIf Dx <> 0 And Dy = 0 Then
    wx = wx + LD * Dx / dt
    ElseIf Dy <> 0 And Dx <> 0 Then
    wx = wx + LD * Dx / dt
    wy = wy + LD * Dy / dt
    End If

    Picture1.FillStyle = FillStyle_Dep
    Picture1.FillColor = Deposition_color
    Picture1.Circle (wx, wy), D_drop / 2, Deposition_color
    Write #4, wx, wy, z2
    Write #5, wx, wy, z2
    dep_num = dep_num + 1
    Call slow

  Next k
x1 = x2
y1 = y2
```

```
ElseIf Abs(dt) < LD And G = 1 Then

x1 = x2
y1 = y2


ElseIf G = 0 And Abs(dt) <> 0 Then
   Picture1.Line (x1, y1)-(x2, y2)
      x1 = x2
      y1 = y2



End If


If G <> 0 Then
z = z2
End If

Loop

Close #1
Close #4
Close #5

End Sub
```

Appendix D6 filtering algorithm

```
Public ()
outfile6 = "c:\deposition_positions.txt"
mainfrm.List1.Visible = False
Lmin = Val(InputBox("Enter the minimun distance bettwen the droplets", "Input Request"))
On Error GoTo HandleErrors

Open outfile5 For Input As #5
Input #5, x1, y1, z1

Open outfile6 For Output As #6
Write #6, x1, y1, z1
Close #6
```

```
Call mainfrm.Picture1.Cls
Call Drawaxis
mainfrm.Picture1.FillStyle = FillStyle_Dep
mainfrm.Picture1.FillColor = Deposition_color
mainfrm.Picture1.Circle (x1, y1), D_drop / 2, Deposition_color

z = z1

Do Until EOF(5)

DoEvents
Er = 0
Call slow

Input #5, x1, y1, z1

      If z <> z1 Then
      Call mainfrm.Picture1.Cls
      Call Drawaxis
      End If

Open outfile6 For Input As #6

Do Until EOF(6)

   Input #6, x2, y2, z2


d = Sqr((x2 - x1) ^ 2 + (y2 - y1) ^ 2)

   If d < Lmin And z1 = z2 Then
      Er = Er + 1
   End If

Loop

Close #6

If Er <> 0 Then
```

```
mainfrm.Picture1.FillStyle = FillStyle_filtr

mainfrm.Picture1.FillColor = Filtring_color
mainfrm.Picture1.Circle (x1, y1), D_drop / 2, Filtring_color

ElseIf Er = 0 Then

Open outfile6 For Append As #6
Write #6, x1, y1, z1
Close #6

mainfrm.Picture1.FillStyle = FillStyle_Dep
mainfrm.Picture1.FillColor = Deposition_color
mainfrm.Picture1.Circle (x1, y1), D_drop / 2, Deposition_color

End If

z = z1
Loop

Close #5


HandleErrors:
If Err.Number = 75 Then
intResponse = MsgBox("file not found", vbOKOnly, "Invalid Path")
Exit Sub
Else
Exit Sub

End If

End Sub
```

Appendix F CAM/RP

```
/**********************************************************************
                    PC23 RESET, READ, WRITE DRIVERS

  The following routines will compile under Borland or Microsoft C.
  They are intended to demonstrate basic communication routines in C.
**********************************************************************/

#include <stdio.h>
#include <conio.h>
#include <stdlib.h>
#include <dos.h>

#defineFAIL      0X20
#define BIT2MASK   0X04
#define READY      0X16
#defineCB        0X60
#define IDB_M          0X10
#define CHAR_READY 0X70
#define ODB      0X8
#define ACK      0XE0
#define ALDONE     0X02
#define BADADDR    0XFF
#define HALT         (CB | BIT2MASK)
#define RESTART      0x40         /* byte to restart the pc21 */
void initialize (void);
void writech (char);
char readch (void);
void writecmd (char *s);
void readanswer (char *s);
void callstay();
int axis, address ;                 /* normally 300 hex */

int main()
{
        char  *message,*answer;
        FILE *fp;
        int ch;
        char *input;
        int true=0,start=0,end=0;
        int counter=0,i;
```

```
int a;
char *fileN;
answer="";
message="";
/*if(argc!=2)
{
        printf("Please Enter command as: File [data file name]");
        return 0;
}*/

/*if((fp=fopen (argv[1],"r"))==NULL)*/
/******
/printf("Enter the file Name: \n");
scanf("%s",fileN);
printf(fileN);
*/
fileN=("c:\\drop1.txt");
if((fp=fopen (fileN,"r"))==NULL)
{
        printf("Unable to open the file.");
        return 0;
}

initialize ();            /* RESET THE PC23 */

printf("\n The following program example demonstrates the basic");
printf("\n use of RESET, READ, and WRITE C drivers for the PC23.");
printf("\n\n The C source file is motorm.C.\n");


while((ch=fgetc(fp))!=EOF)
{
        if(ch==34)
        {
                if(true==0) {true=1;start=1;end=0;}
                else
                        { true = 0;start=0;end=1;}
                if(true == 0)
                        free(input);
        }
```

```
		if(start==1)
		{
			input=(char *) malloc(200*sizeof(char));
			counter=0;
			start=0;
		}
		if (true == 1)
		{
			input[counter]=ch;
			 counter++;
		}


		if(end==1)
		{
			printf("\n");
			input[counter]=34;
			message =(char *) malloc((counter) * sizeof(char));  /* malloc
is used for memory allocation */
			for(i=0;i<counter;i++)
			message[i]=input[i];
			printf("%s",message);
			writecmd(message);
			while((inportb(address+1) & ALDONE) != ALDONE);
			readanswer(answer);
			printf("\n%s",answer);
			answer="";
			message="";
	}

	fclose(fp);	/*closing the open file */


	/*message=" 3PR ";		/* AXIS 3 POSITION */
	/*writecmd(message);
	readanswer(answer);
	printf("\n ");
	printf(answer);
	printf("\n");*/
  return 0;
```

```
}

/* *********************************************************************
  INITIALIZE: RESET THE PC23 BOARD.  ASSURING THAT THE BOARD IS
         READY TO ACCEPT COMMANDS FROM THE USER PROGRAM.
*********************************************************************/

void initialize ()
{
        char i;
        int status_addr=0;
        unsigned char statbyte;
        /*printf("\n\n");
        printf("Enter the Decimal value Board Address for the PC-23 : ");
        /*scanf("%d",&address);*/
        address=768;
        if ((address < 768) || ( address > 812))
                {
                printf ("\n\nInvalid address, check PC-23 dipswitches\n\n");
                exit(1);
                }
        status_addr=address+1;
        outp(status_addr,HALT);
                 /* initialize procedure */
        while(!((statbyte=inp(status_addr)) & FAIL) );
        if(statbyte==BADADDR)
                {
                printf ("\n\nInvalid address, check PC-23 dipswitches\n\n");
                exit(1);
                }
        outp(status_addr,RESTART);
        outp(status_addr,CB);
        while( ( (statbyte=inp(status_addr)) & READY) != READY );
}
```

```
*****************************************************************
WRITECH: WRITES A SINGLE CHARACTER TO THE PC23. PC23
COMMANDS ARE
            GENERATED BY SENDING MULTIPLE CHARACTERS TO IT.
*****************************************************************
void writech ( char alpha )
{
        while (!(inp(address+1) & IDB_M));
        outp (address,alpha);
        outp (address+1, CHAR_READY);
        while (inp(address+1) & IDB_M);
        outp(address+1,CB);

        while (!(inp(address+1) & IDB_M));
        return;
}

/****************************************************************
READCH: READS ONE CHARACTER OF A PC23 RESPONSE TO A STATUS
                              REQUEST.
                RETURNS THE CHARACTER RESPONSE.
****************************************************************/
char readch()
{
        char alpha=0;
        while (!(inp(address+1) & ODB));
        alpha = inp(address);
        outp (address+1,ACK);
        while ((inp(address+1) & ODB));
        outp (address+1,CB);

        return(alpha);
}
/****************************************************************
        WRITECMD: WRITES A COMMAND STRING TO THE PC23.
*****************************************************************
void writecmd(char *s)
{
        while (*s)
                writech (*s++);
```

```
        return;
}
/* ************************************************************************
READANSWER: READS A COMPLETE PC23 STATUS REQUEST RESPONSE
                              STRING.
************************************************************************
void readanswer (char *s)
{
        while ((*s++ = readch()) != 13);
        *s = '\0';
        return;
}
void callstay()
{
delay(2000);
}
```