

**Military Technical College
Kobry El-Kobbah,
Cairo, Egypt.**



**18th International Conference
on Applied Mechanics and
Mechanical Engineering.**

ENHANCEMENT OF SLICED LAYER CONTOUR FOR RECONSTRUCTING A 3D MODEL USING SOLID FREEFORM FABRICATION

M. Hamoud *

ABSTRACT

Nowadays, Solid Freeform Fabrication (SFF) takes a great attention by creating complex solid objects directly from geometric models without specific tooling information. SFF also referred to layered manufacturing (LM) which builds up 3D objects by successive 2D layer deposition after exporting it as an STL file format from its CAD environment.

This paper aims at overcoming the approximation problem of 2D layer contour from sliced STL model. The author used a Lagrange interpolation method to increase the point's coordinates of the sliced layer contour in order to reconstruct an accurate and near net contour of the original sliced CAD model. This method reduced the error between the original sliced CAD model and the actual reconstructed layer contours to 0.006%.

KEY WORDS

Solid Freeform Fabrication, Dimensional Error, Slicing a 3D model, Lagrange Interpolation.

* Assistant Professor, Faculty of Engineering, Helwan University, Cairo, Egypt,
Dr_hamoud2015@h-eng.helwan.edu.eg.

NOMENCLATURE

A:	Layer area (mm ²)	X _i :	X- coordinates of a layer contour
F:	Facetres value	X _{max} :	Maximum X-coordinate for the layer contour
L _t :	Layer thickness (mm)	X _{min} :	Minimum X-coordinate for the layer contour
N:	Total number of sliced contour points	Y:	Y- coordinates of a layer without redundancy
O:	Orientation angle (degree)	Y _i :	Y- coordinates of a layer contour
P(X):	Polynomial function	Y _{max} :	Maximum Y-coordinate for the layer contour
P _i :	Point coordinates	Y _{mean} :	Y- coordinate for layer contour mid-point of the
P _j :	Next point coordinate in the layer contour	Y _{min} :	Minimum Y -coordinate the layer contour
X:	X- coordinate of a layer without redundancy		

INTRODUCTION

Solid free form fabrication (SFF) comprises a group of technologies used to build physical parts by adding material in a layer-by-layer fashion from a computer-aided design (CAD) file, as opposed to subtractive manufacturing methods, such as machining. Over the last three decades, many SFF technologies have been developed for the production of polymeric, metallic or ceramic parts [1]. Because this technologies are being increasingly used many applications, The technology is also known by several other names like Additive Manufacturing (AM), Rapid Manufacturing (RM), Rapid Prototyping (RP), Layered Manufacturing (LM), digital fabrication, 3D printing, , solid imaging, laser prototyping, free form fabrication (FFF), Desktop Manufacturing, Direct CAD Manufacturing, and Computer Automated Manufacturing [2]. One recent aspect of product data communication is the communication standard between CAD systems and SFF systems. Here, a format called STL (Standard Transform Language) file [3].

A STL file is a triangular representation of a 3D surface geometry. The surface is broken down into series of small triangles (facets) as shown in Fig. 1. A perpendicular direction and three points representing the vertices of the triangle are shown in (Fig. 2). A slicing algorithm that uses to slice the 3D CAD model is shown in (Fig.3). STL helps simplify the process of transferring work piece geometry from one system to another. A triangular mesh generated by tessellation of the boundary surface of 3D solid is a very simple surface representation. For engineering applications, the mesh must also contain the information of which side of a triangle contains the interior of the solid. Data of such triangular meshes are suitable for 3D model description, and the STL format has become standard for data input of all types of SFF systems [4]. On the other hand, several disadvantages of the STL file exist. First, the STL file is many times larger than the original CAD data file for a given accuracy parameter. Second, the STL file carries much redundancy information such as duplicate vertices and edges shown in (Fig.4). Third, the subsequent slicing of large STL files can take many hours. Finally, STL files as they

contain no topological data as a result they tend to create polygonal approximation models [5].

The presented paper deals with the approximation problem for the sliced layer from the STL model.

LITERATURE REVIEW

There are several attempts to help in solving the STL file format problems. Hamoud et al. [4] presented an algorithm to orient and slice a CAD model for rebuilding using RP. In this paper, the authors proposed an algorithm to read the STL file, remove the undesired data from the file, extract the required coordinates that describe the complete CAD model and remove the redundant coordinates from the file. A presentation of algorithm used for controlling the orientation of CAD model by any chosen angle and slicing the oriented CAD model by specified layer thickness respectively was also discussed. This paper helps in building a specialized software that read, orient and slice any STL model. Hamoud et al. [5] presented an algorithm to predict and minimize the dimensional error of building a model in two axis (X and Y), with different values of layer thickness. Furthermore, the proposed algorithm suggested the best part building orientations and slicing height, which satisfies the minimal dimensional error. Badino et al [6] presented the computation method of surface normal from a point cloud that was collected from scanned object. This paper helps in applications for many 3D robotics and automotive problems, including terrain estimation, mapping, navigation, object segmentation, and object recognition.

Teng et al. [7] presented a new neighborhood graph definition of point clouds, called visible neighborhood graph. A local construction scheme using visibility information near each sample point was developed, and the neighbors were defined based on a convex hull computation in a dual space. Their method was able to approximate the underlying surface on which the point cloud was sampled, and can provide accurate neighborhoods in regions of close by surface sheets. Yin [8] presented in this paper an extended STL file format. Differing with existing solutions, it proposed a new format to produce and store triangles. The format uses a cluster unit composed of several triangles. Direct generation of the extended STL from the scanned data had a great advantage in that it can reduce the time and error in modeling process. In order to obtain the format from unorganized point cloud, a new triangulation algorithm was introduced. Shengjun et al. [9] proposed a method to reconstruct a surface from unorganized points. The method connected the point to form a mesh. After generating the triangular mesh surface and cleaning its topology, a local search based algorithm was conducted to find the closest triangle to every input point and then specify their orientations. These previous efforts provided good contribution in solving some of STL file problems but they didn't present any algorithm to improve the layer contour nor didn't present any detailed algorithms to help the researchers to make software to study the different parameters in SFF without the experimental work.

PROBLEM DEFINITION AND AIM OF RESEARCH

An STL file is the standard data format between CAD systems and SFF systems.

Despite of the advantages of the STL file, it has several disadvantages. One of these disadvantages related to the layer accuracy, which will affect the whole part accuracy, is an approximation problem (Fig.5). Due to this deficiency, object distortions may be produced. The approximation method is not well defined; this means that the approximation can lie inside or outside the object according to whether a surface is convex or concave as shown in Fig.6.

The presented paper deals with the polygonal approximation problem of an STL model. The author present an algorithm which apply the Lagrange interpolation to increase the points that represent each individual 2D layer shape after slicing operation to increase the original CAD layers and enhance the dimension accuracy of the actual building layers. Consequently, the reconstruction of the physical 3D model will be enhanced.

LAGRANGE INTERPOLATION METHOD

Interpolation is a method for estimating the value at a query location that lies within the domain of a set of sample data points. Sample data sets defined by locations x_i and corresponding values y_i can be interpolated to produce a function of the form $P(X)$. This function can then be used to evaluate a query point X , to give $F(X)$. This is a single-valued function; for any query, X within the domain of X it will produce a unique value Y . The sample data is assumed to respect this property in order to produce a satisfactory interpolation. One other interesting characteristic is that the interpolating function passes through the data points. This is an important distinction between interpolation and curve/surface fitting. In fitting, the function does not necessarily pass through the sample data points.

Problem Formulation

Lagrange gave the following interpolation polynomial $P(X)$ of degree N given points coordinate (x_i, y_i) of the sliced layer.

$$y = p(X) = \sum_{i=1}^N y_i l_i(X) \tag{I}$$

where the $l_i(X)$ are the Lagrange Basis Polynomials, defined by

$$l_i(X) = \prod_{\substack{0 \leq m \leq k \\ m \neq i}} \frac{X - x_m}{x_i - x_m} \quad \text{Where } k = N-1 \text{ and } m \neq i \tag{II}$$

Constrains

1. The layer contour coordinates should be in ordered form.
2. The layer contour should not contain redundant coordinates.
3. The shape of contour shouldn't be closed.

PROPOSED WORK

The work in this paper is an extension to some previous (Reference No.4) work that starts by reading the STL file, removing the undesired data from the file, extracting the required coordinates that describe the complete 3D CAD model, determining its building orientation and slicing the oriented CAD model by a pre-specified layer thickness. The previous work output was the contour point's coordinates for each layer.

The proposed algorithm starts with the following procedure:

1. Reading the points coordinates $[x_i \ y_i]$ of the sliced layer contour.
2. Removing the redundant points coordinates by applying the following sub-procedure:
 - 2.1 Reading the first point coordinate as P_i , where $P_i = [x_i \ y_i]$.
 - 2.2 Reading the next point coordinate as P_j , where $P_j = [x_j \ y_j]$.
 - 2.3 If $P_i = P_j$ then, remove P_j from sliced layer contour points.
 - 2.4 If P_j is reached to the last coordinate, then ending the sub-procedure.
 - 2.5 Saving the layer points coordinates without redundancy as $[X, Y]$.
3. Determining the maximum and minimum coordinates of X and Y as X_{max} , X_{min} , Y_{max} and Y_{min} .
4. Calculating the mean coordinate of Y axis Y_{mean} , where

$$Y_{mean} = \frac{Y_{max} + Y_{min}}{2}$$

5. Separating the layer contour into upper and lower part according to its Y coordinates as the following:
 - 5.1 The upper part of contour points coordinates will satisfy the following rule.
All points that have $Y \geq Y_{mean}$ are ranged from X_{max} to X_{min} .
 - 5.2 The lower part of contour points coordinates will satisfy the following rule.
All points that have $Y < Y_{mean}$ are ranged from X_{min} to X_{max} .
6. Increasing the layer contour by applying the Lagrange interpolation method on each part of layer individually.
7. Saving the new interpolating points that represent the enhanced shape of layer contour.
8. Repeating the previous procedure for all points of the reaming layer contours in order to enhance the complete sliced 3D model.

Figure 7 shows a flow chart of the proposed algorithm to simplify the programming it and integrate it as a part of machine software. The system is developed on core i7, 2.2 MHZ, PC with windows 7, Matlab V 2011a.

APPLICATION STUDY

In Case of 2D Layer

The proposed algorithm is applied on a layer contour of cylinder that has 50 mm in radius after representing it in solid modeling and exporting its ASCII STL file.

Although the original CAD layer area was supposed to be 7854 mm² with circular shape, the sliced layer contour coordinates gave 8 points, which represent a polygon with area of 7500 mm². The total error is 354 mm² (5%) with polygonal shape as shown in Fig.8 and Fig.9. By increasing the contour points as 30 points on the upper part and 30 points on the lower part, the area reached to 7803 mm² and the error reduced to 51 mm² (0.006%) in the total area. The enhancement of the layer is noticed as shown in Fig.10. The data and results of applying the algorithm with different number of points are presented in table 1. The degree of enhancement in the shape of layer contour is demonstrated in Fig.11. The Relation between the number of new coordinates and the resulting error is shown in Fig.12.

In Case of a 3D Model

A sphere solid model with 100 mm in diameter, and centered at (X = 100, Y = 100 and Z = 100 mm). The case is proposed to show the effect of the degree of STL file accuracy on the sliced layer contour. The study is depending on changing the value of facetres that will ranging from 0.01 to 10 and exporting the STL file for each value. Afterward, each STL file will be reading and slicing to give the number of points included in the STL file, the number of the existing layers, and the number of points in each layer after removing the redundancy. Figure 13 shows the STL mode with facetres =0.01. The following data are obtained:

Number of points with redundancy is 144, number of facets is 48, number of points without redundancy is 26, number of existed layers is 5 and the maximum number of contour points is 8, which represent a poor layer shape. The detailed data presented in Table 2.

Figure 14 shows the STL mode with facetres =0.35. The following data are obtained: Number of points with Redundancy is 2688, number of facets is 896, number of points without redundancy is 450, number of layers is 17 and the maximum numbers of points that represent the layer contour is 32 that represent a poor layer shape. The detailed data presented in Table 3.

Because STL file contains a huge number of redundant points at a higher value of facetres, the author applied curve- fitting to relate the Facetres value (F) with maximum number of points in each layer contour as shown in Fig. 15. The mathematical equation that predict the maximum number of contour points is expressed in equation (III).

$$\text{Max. No. of Points} = (55.175 * F) + 9.8612 \quad \text{(III)}$$

Table 5 lists the results of applying the predication model at different values of F. The predicted maximum number of contour points at higher value of Facetres (F=10) is 500. It is noticed that the maximum number of contour points is remaining constant regardless the model volume. Accordingly, the error between sliced CAD layer contour and the reconstructed contour. Therefore, it is necessary to apply the proposed algorithm to smooth the polygonal approximation problem of layer contour. In addition, if STL file was exporting with bad accuracy, the proposed algorithm can get a more accurate of the reconstructing layer contour and a smoother 3D physical model near to 3D CAD model.

CONCLUSION

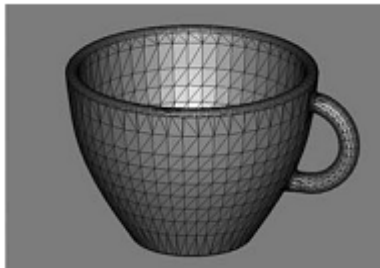
The proposed work presents an applied of Lagrange interpolation method to increase the accuracy of the layer contour shape and to minimize the error between the sliced layer from STL model and the actual/reconstructing layer. Through this research, the author concluded that:

- Lagrange Interpolation method doesn't deal with closed contour that is why the layer should split into two halves.
- By a small increasing in the number of the interpolating points, the geometrical error between the original CAD layer and actual building layer will decrease.
- The geometrical error of layer decrease until the layer reaches the nearest shape to the original CAD layer. After that, any increase in the number of the interpolating points will have no effect.
- Lagrange method provides an advantage that it generates a function that passes by the original points of the sliced model. That is how an accurate 3D physical part can be produced.
- The proposed algorithm has a significant effect on the Solid Free Form fabrication through its benefits. By applying the algorithm, the layers can built with high dimension accuracy, the polygonal problem in curvature surface is solved, the problem of STL file accuracy is solved, and it can be increase the points of scanned data from reverse engineering to create triangles of the whole STL model.

REFERENCES

- [1] J. Gonzalez-Gutierrez, D. Godec, R. Guráň, M. Spoerk, C. Kukla and C. Holzer, "3D Printing Conditions Determination For Feedstock Used In Fused Filament Fabrication (FFF) Of 17-4ph Stainless Steel Parts", METABK 57(1-2) PP 117-120, (2018)
- [2] M. Hamoud Ahmed, "Modeling and Optimization of Rapid Prototyping", M.Sc. Thesis, Mechanical Engineering Dept., the Faculty of Engineering, Helwan University, Egypt, (2008).
- [3] M. szilvasi – Nagy, and G. Matyast, "Analysis of STL File", Mathematical Modeling, Vol. 38, PP 945 – 960, (2003).
- [4] Hamoud M., EL-Wahab, A. I., Barakat, A. and Khalid, M. , " A Simple Algorithm To Orient And Slice The CAD Model For Rebuilding Using Rapid Prototyping ", proceeding of 9th Cairo University International Conference on Mechanical Design & Production (MDP-9), Cairo – Egypt, January 8-10, PP 298 – 312, (2008).
- [5] Hamoud M., EL-Wahab, A. I. and Barakat, A.," A New Algorithm To Predict And Minimize The Fabricating Error Of Building A 3D Model Using Rapid Prototyping", The Fifth International Exergy, Energy and Environmental conference, IEEEES-5, Luxor, Egypt, December12-15, (2011).
- [6] H. Badino, D. Huber, Y. Park and T. Kanade, "Fast and Accurate Computation of Surface Normals from Range Images", International Conference on Robotics and Automation (ICRA), Shanghai, China, May (2011).

- [7] Teng Ma, Xiang Long, Lu Feng, Pei Luo and Zhuangzhi Wu " Visible Neighborhood Graph Of Point Clouds", Graphical Models, Vol. 74, PP 184–196, (2012).
- [8] Yin Z. W., "Direct Generation of Extended STL File from Unorganized Point Data", Computer-Aided Design, Vol. 43, PP 699–706, (2011).
- [9] Shengjun Liu and Charlie C.L. Wang, "Orienting Unorganized Points for Surface Reconstruction ", Computers & Graphics, Vol. 34, PP 209–218, (2010).



<pre> solid print facet normal 0.00000e+00 1.00000e+00 0.00000e+00 outer loop vertex 0.00000e+00 0.00000e+00 2.00000e+01 vertex 0.00000e+00 0.00000e+00 0.00000e+00 vertex 1.00000e+01 0.00000e+00 2.00000e+01 endloop endfacet facet normal 0.00000e+00 1.00000e+00 0.00000e+00 outer loop vertex 1.00000e+01 0.00000e+00 2.00000e+01 vertex 0.00000e+00 0.00000e+00 0.00000e+00 vertex 1.00000e+01 0.00000e+00 0.00000e+00 endloop endfacet </pre>	
--	--

Fig. 1. STL format.

Fig.2. A sample of STL file.

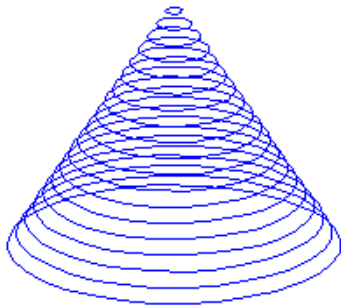


Fig.3. Sliced model.

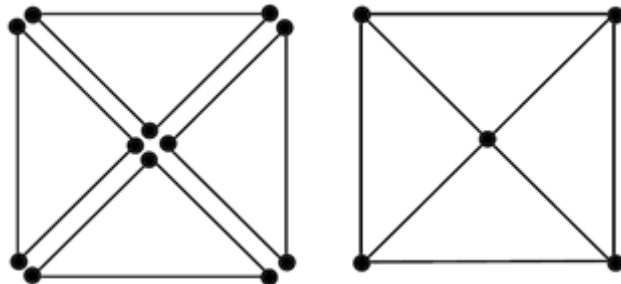


Fig.4. Redundancy information in STL format.

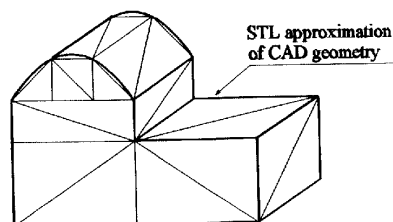


Fig.5. Approximation problem of STL model.

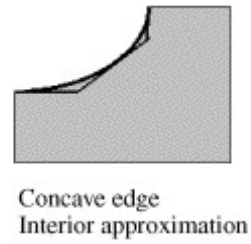
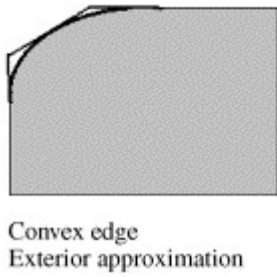


Fig.6.a. Approximation of convex edge

Fig.6.b. Approximation of concave edge

Fig.6. Effect of the approximation on sliced layer contour.

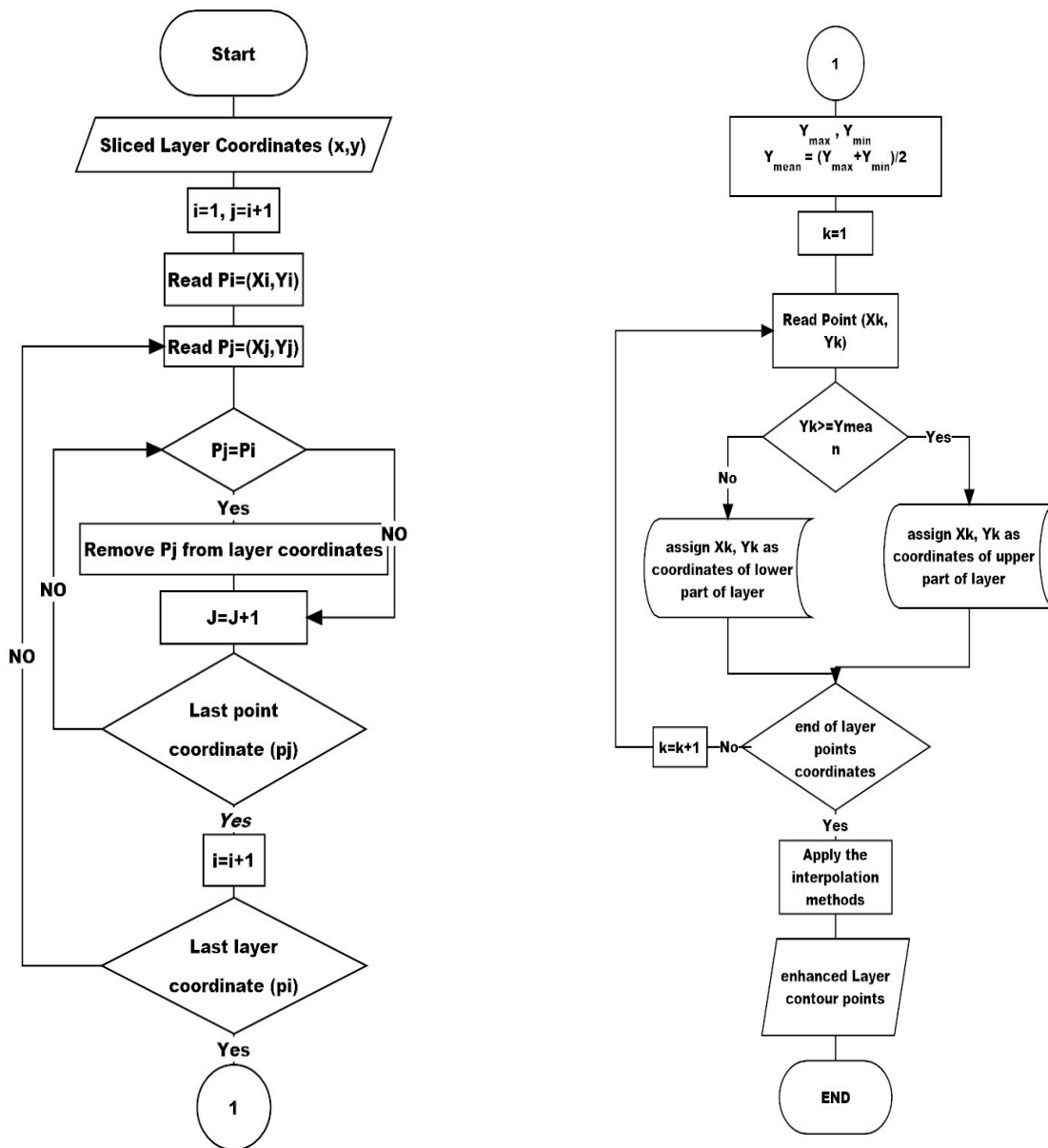
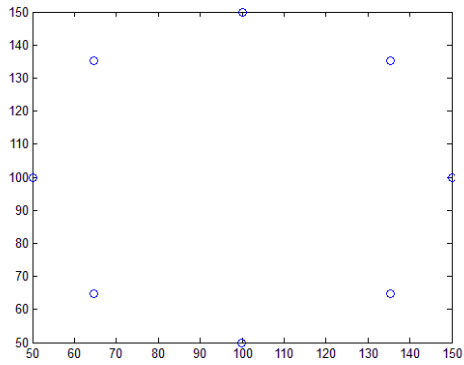


Fig. 8. The presented algorithm.



All dimensions are in mm

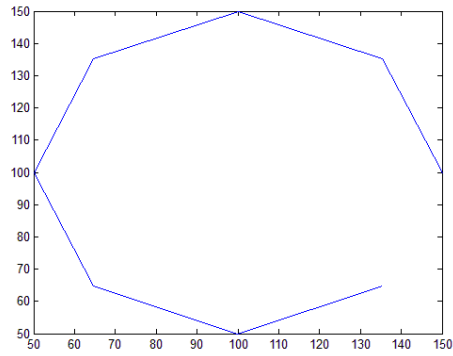
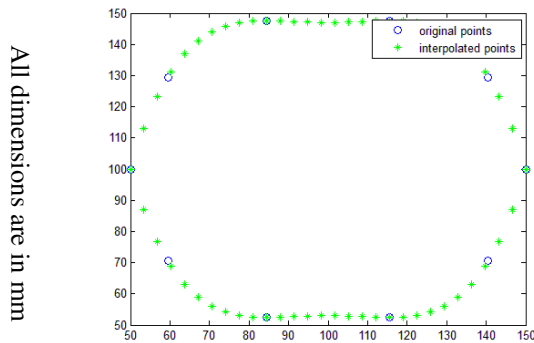
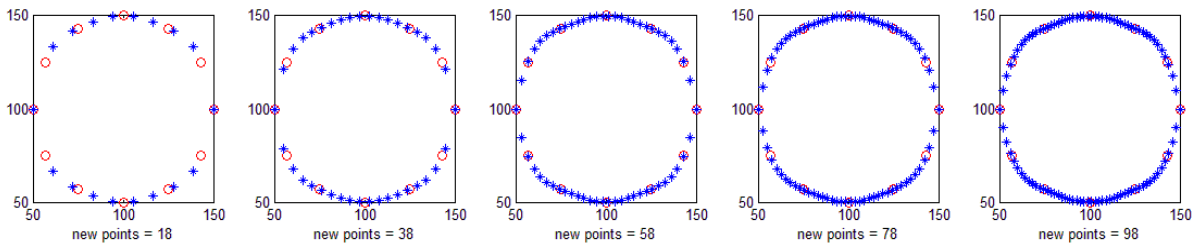


Fig.8. Sliced layer represented by 8 points **Fig.9.** Approximation of layer contour



All dimensions are in mm

Fig.10. The interpolated points pass through the sliced layer points.



All dimensions are in mm

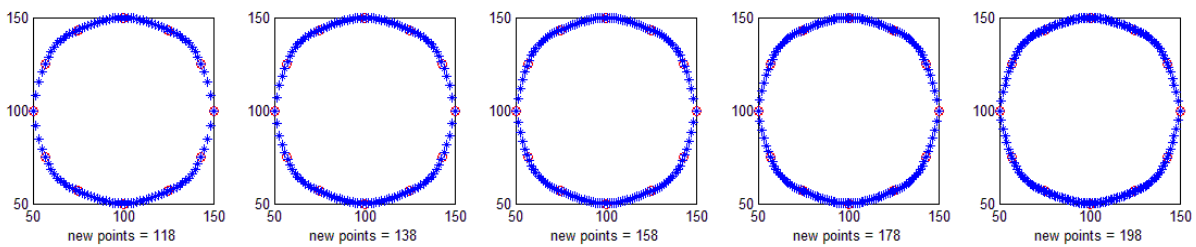


Fig.11. The effect point increasing on the layer contour shape.

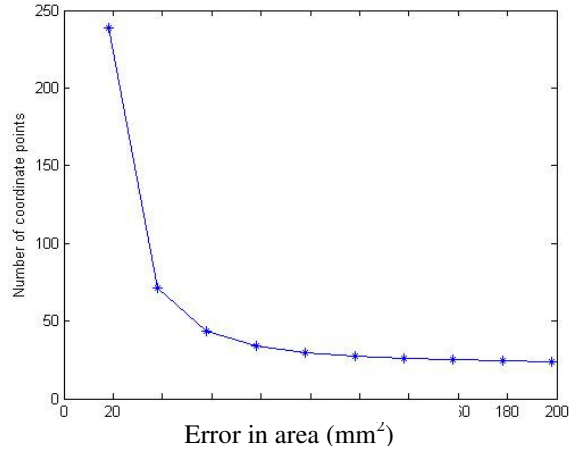


Fig.12. The relation between the increasing of points contour with the resulting error

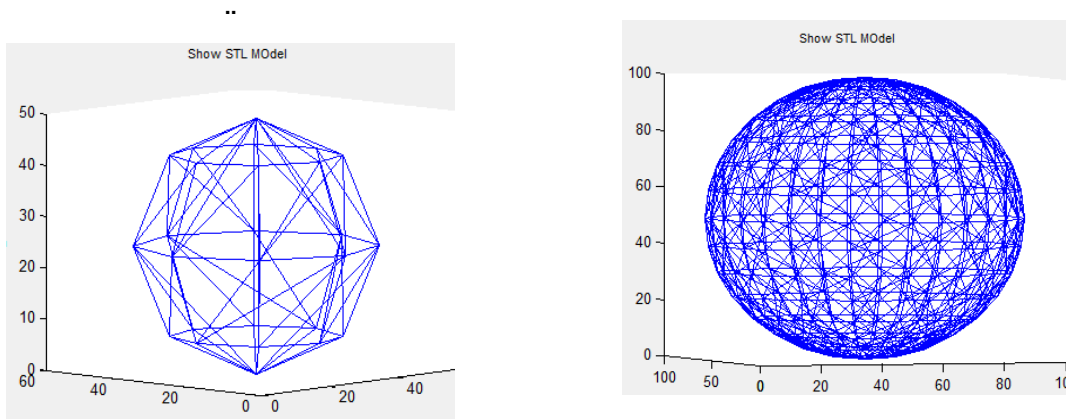


Fig.13. STL model with facetres = 0.01.

Fig.14. STL model with facetres = 0.35.

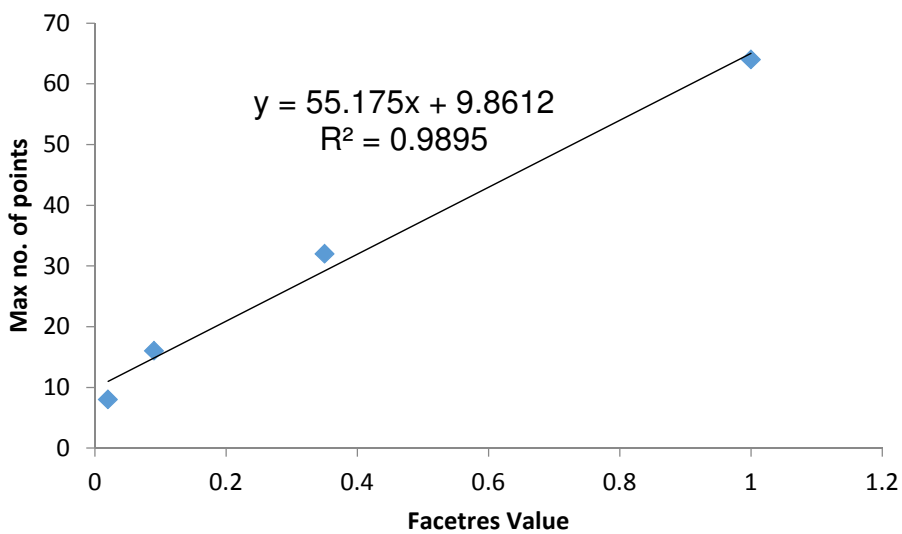


Fig.15. The relation of facetres value with the max. no. of points.

Table 1. The result of applying a different number of interpolating points using Lagrange method

Total number of added points	Area after enhanced Layer (mm ²)	Error in areas between STL model layers and the enhanced layers
18	7615.358	238.622
38	7782.545	71.436
58	7810.705	43.276
78	7820.209	33.771
98	7824.523	29.457
118	7826.838	27.142
138	7828.222	25.758
158	7829.115	24.865
178	7829.725	24.256
981	7830.159	23.822

Table 2. Solid model data for each layer

Layer At Z =	Number Of Points At Each Layer	Layer Thickness
50	1	0.0
64.644661	8	14.644661
100	8	35.355339
135.355340	8	35.355340
150	1	14.644660

Table 3. Solid model data for each layer at facetres = 0.35

Layer At Z =	Number Of Points At Each Layer	Layer Thickness
50	1	0.0
50.960736	16	0.960736
53.806023	32	2.845287
58.426519	32	4.620496
64.644661	32	6.218142
72.221488	32	7.576827
80.865828	32	8.644340
90.245484	32	9.379656
100	32	9.754516
109.754520	32	9.754520
119.134170	32	9.379650
127.778510	32	8.644340
135.355340	32	7.576830
141.573480	32	6.218140
146.193980	32	4.620500
149.039260	16	2.845280
150	1	0.960740

Table 4. Shows the summarization of the relation between the facetress value (F) and the maximum number of points that represent the layer.

F	0.01	0.02	0.03	0.04	0.05	0.06
Max. No. points	8	8	16	16	16	16
F	0.07	0.08	0.09	0.1	0.15	0.2
Max. No. points	16	16	16	32	32	32
F	0.25	0.3	0.35	0.4	0.45	0.5
Max. No. points	32	32	32	64	64	64
F	0.55	0.6	0.7	0.8	0.9	1
Max. No. points	64	64	64	64	64	64

Table 5. The predication model gives the following results.

F	1.5	2	2.5	3	3.5	4
Pred. Max. No. points	90	118	145	173	200	228
F	4.5	5	5.5	6	6.5	7
Pred. Max. No. points	255	283	310	338	365	393
F	7.5	8	8.5	9	9.5	10
Pred. Max. No. points	420	448	475	503	530	558