



Direct slicing techniques of 3D surface model in layers manufacturing

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Received 23 Jan. 2018; Received in revised form 6 Feb. 2018; Accepted 20 Feb. 2017; Available online 1 July 2018

Abstract

Layered Manufacturing (LM) which is the core of Rapid Prototyping (RP) the part is generating using layer-by-layer addition of the material. Where slicing of the Computer-Aided Design (CAD) models on a part to be produced is one of the important steps. Direct slicing a three-dimensional (3D) graphic model into layers of two-dimensional (2D) contour plots is an essential step for all rapid prototyping (RP) machines. This paper establishes a base surface parameterization using direct slicing strategy for based on a vertical sectional design technique using different layers thickness at 3D surface and study the effect of slice thickness on the final 3D model accuracy. The proposed method directly extracting 3D to vertical sectional contours from mathematical definition of parametric surface and converting to (2D) layers, the final surface achieved by manufacturing layers using Computer Numerical Control (CNC) laser cutting machine. A measuring method has been proposed and implemented to measure the accuracy of the final 3D surface. statistical method of error assessment and similarity factor have been implemented in this work to show the efficiency of the proposed work and comparing between original CAD models and prototyping models. The results of similarity factor show that, (84.317%) for 2.5 mm Bezier model, (72.492%) for 4mm Bezier model, (61.012%) for 8mm Bezier model.

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Keywords: Rapid prototyping; Layered manufacturing; Slicing method.

1. Introduction

Rapid prototyping (RP) refers to a family of modern technologies in which three-dimensional solid objects are fabricated under computer control [1].

RP techniques led to reducing manufacturing time up to (30-50 %) regarding of shapes complexity [2, 3]. RP methods leading to reduce production cost, because it is working on eliminating errors or flaws early in production development steps, so that RP fast and common design repetitions [4]. Additive processes using layered manufacturing describe the family of modern RP techniques, in RP processes, the data of manufacturing shape can be obtained from computer aided design (CAD) represented model [5, 6]. The model is then sliced into numbers of layers. In this process, horizontal planes cross CAD model to produce a series of slices (cross sections), construct group of curves that signify the material boundaries of the surfaces to be generated. Then, tool path generated depending on boundaries data of LM hardware's [1]. In this paper establishes a base surface parameterization using direct slicing strategy based on a vertical

sectional layer's design technique using different layers thickness at 3D surface and study the effect of slice thickness on the final 3D model accuracy.

2. Direct slicing of 3D surface

Direct slicing uses the exact contour of a CAD model as the input data more accurate method. It is eliminating the limitations of STL and avoids tessellation error and data repair associated with the use of an STL model [3, 7].

2.1 Bi-Cubic Bezier Patch

The mathematical representation of 3D Bi-Cubic Bezier patch defined as [8, 9]:

$$P(u, w) = \sum_{i=0}^3 \sum_{j=0}^3 P_{ij} B_{i,3}(u) B_{j,3}(w) \quad (1)$$

where p_{ij} is the ij -th control points, $B_{i,3}$ and $B_{j,3}$ is the basis function of the Bi-Cubic Bezier patch in (u) and (w) direction, defined recursively as:

$$B_{i,n}(u) = \binom{n}{i} u^i (1-u)^{n-i} \quad (2)$$

So $B_{j,3}$ has the same definition, Denoting the familiar binomial coefficient function, or binomial distribution from probability and statistics [8, 9]:

$$\binom{n}{i} = \frac{n!}{i!(n-i)!} \quad (3)$$

The previous formulation of Bezier patch can be invested using MATLAB to represent a graphical 3D surface representation. Figure 1 illustrates free form Bi-Cubic Bezier patch used in this work.

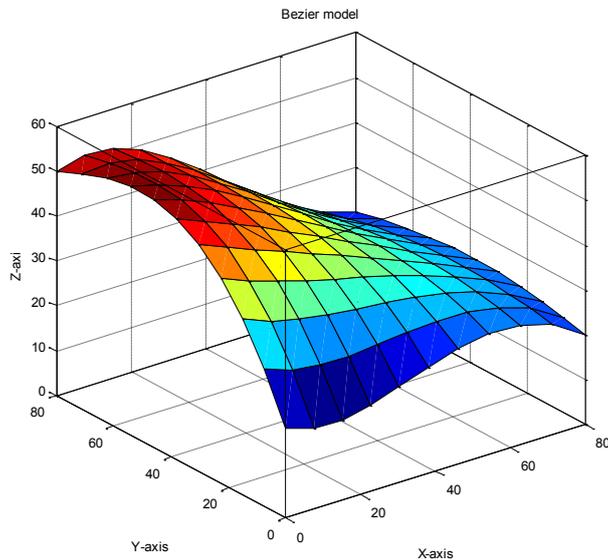


Figure 1. Bi-cubic Bezier patch.

2.2 Slicing of the 3D CAD surface

A slicing procedure has been applied with different offset values (layer thickness) for the surface. These values are selected as 2.5, 4 and 8mm, these values were chosen for making layers with thickness mentioned to reconstruct the proposed 3D Surface. The slicing process for selected surface based on the values of (u) and (w) surface direction and there incremental values ($\Delta u, \Delta w$). Where the (u) parameter is

responsible of vertical cross sections boundary and (w) parameter for thickness values or vice versa. The user can control these values to get the required data in the process of layers fabrication. The dimensions of Bi-Cubic Bezier surface were 80×80mm. Therefore, for (8mm) layers thickness slicing models to (10) vertical cross sections, for (4mm) layers thickness (20) vertical cross sections and for (2.5mm) layers thickness (32) vertical cross sections to reconstruct models later and produced the prototypes. The slicing process was implemented using MATLAB software for easy access to the data required in the process of creation of the layers. Figures 2, 3 and 4 illustrates the process of slicing Bezier to the thickness of proposed layers.

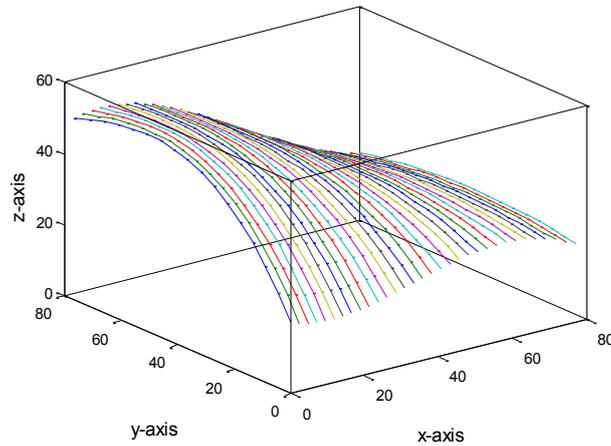


Figure 2. 2.5 mm slicing thickness Bezier CAD model.

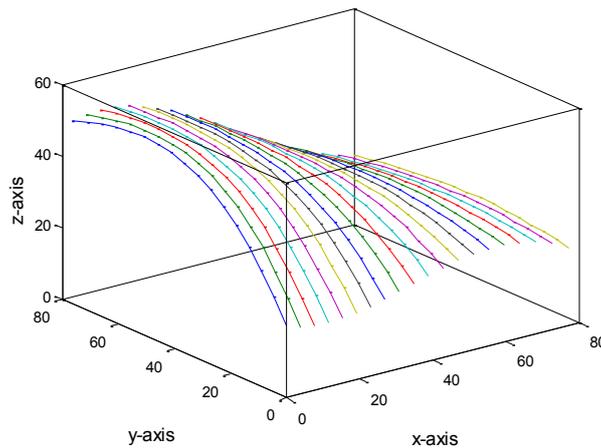


Figure 3. 4 mm slicing thickness Bezier CAD model.

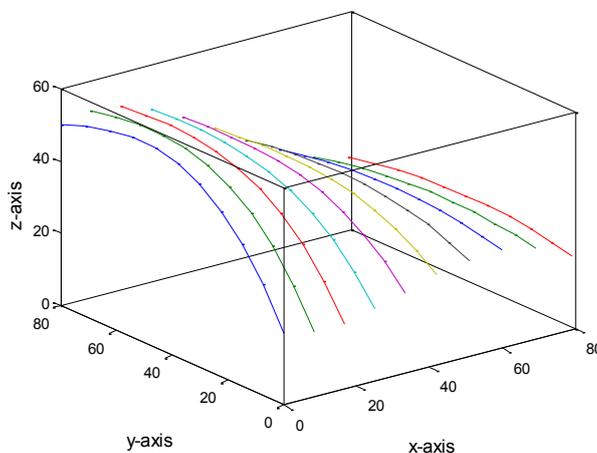


Figure 4. 8 mm slicing thickness Bezier CAD model.

2.3 Contour layers tracing

To complete the process of creating the layers, a proposal to work was the use of AutoCAD software for the creation of the layers using data obtained from MATLAB for the slicing vertical cross sectional, and thus slab grid is generated and 2D slab model was obtained in each layer as shown in Figure 5, this figure illustrates example of creation of layers for proposed Bezier surface. The boundary pixels are identified and boundary of the layers of surface is traced. When completing the process of layers creation, these layers were saved as DWG file format. The purpose of this is to export layers forms for the model to CorelDraw program which is the main key to linking between the final shape of the layers designed for each slice thickness surface and CNC laser cut machine. Figure 6 illustrates the final layers collect by CorelDraw.

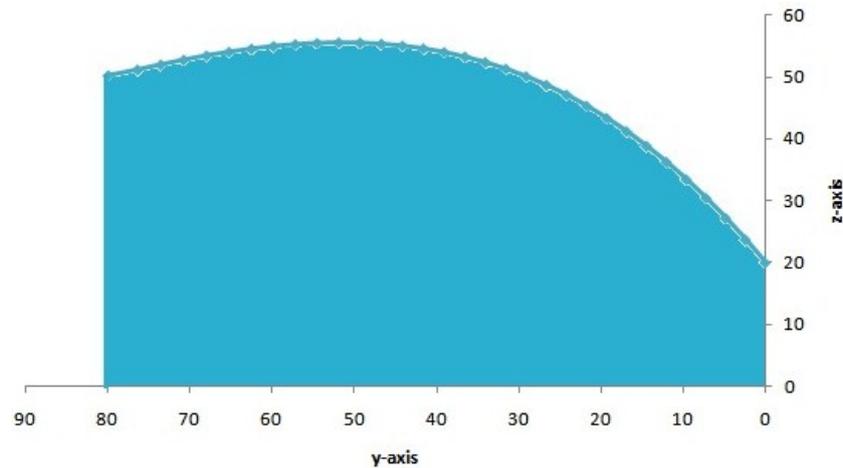


Figure 5. An example of Bezier surface layer designed by AutoCAD.

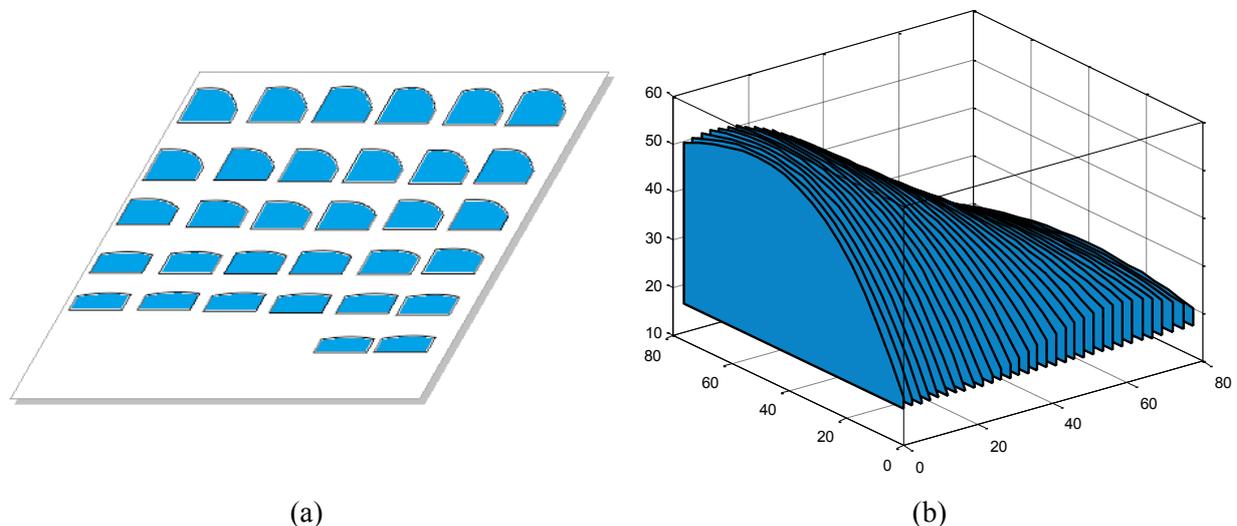


Figure 6. (a) 2.5mm thickness layers of Bezier model collect by CorelDraw; (b) Vertical cross sections model in MATLAB.

3. Cutting set-up

A typical commercial laser for cutting materials would involve a motion control system to follow a CNC or G-code of the pattern to be cut into the material [10]. A Jinka laser cutting machine which is available in local markets was used in this work to cut the different layers thickness. The machine was provided with a digital screen to readout speed, power and cutting time of the process. All experiments were carried out on sheets of Acrylic plastic with thickness 2.5, 4 and 8 mm by using CNC laser cutting machine. The cutting process starts by positioning of sheet material for each model with selected thickness on the bed of laser machine. Then the final window of layers designed by CorelDraw for each surface sending to laser cut program that convert the DWG file format to PLT file format where the machine can read and start the

cutting process. Table 1 illustrates the power, speed of nozzle machine and the cutting time consuming in the process.

Table 1. Specification of cutting process.

Property	2.5mm surface	4mm surface	8mm surface
Number of layers	32	20	10
Speed of nozzle machine	7mm/min	4mm/min	2.4mm/min
Power of machine	3.92kw	3.92kw	3.92kw
Cutting time (Minute)	11:45	10:53	10:14

4. Assembly

Upon completion of the cutting layers process, a base with a square pocket groove has been designed and implemented to assemble surfaces. This has been done with blocks of Teflon material machined by conventional milling machine. Figures 7, 8 and 9 illustrates final prototype models.

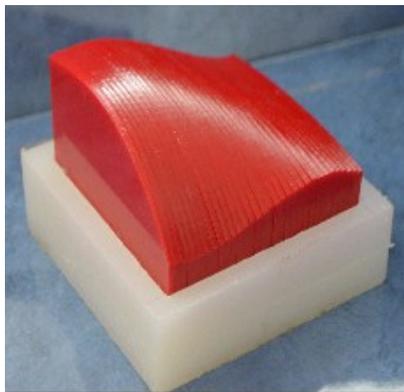


Figure 7. 2.5 mm reconstructed Bezier model.

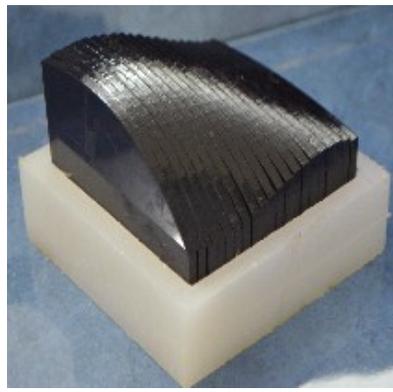


Figure 8. 4 mm reconstructed Bezier model.

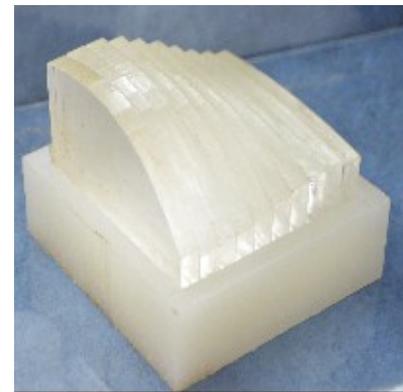


Figure 9. 8 mm reconstructed Bezier model.

5. Measuring

A measuring method has been proposed developed and implemented to measure the accuracy of the 3D surfaces that have been created. Measuring was done by using the digital readout of two axes [X&Y] conventional vertical milling machine that is available in the cutting Lab/Department of Production Engineering. & Metallurgy/University of Technology. The machine has been equipped with a digital touch probe which has an accuracy of (0.001) mm inserted instead of the tool in the Z-axes, so the machine movement could be digitally controlled through three axes which is [X, Y&Z], that make the machine able to measure the accuracy of the 3D models. At the begin a clamping device has been calibrated and fixed on the table of the conventional milling machine to clamp the models for measurement. The measurements of prototyping models have been done by moving the styli of indicator instrument on the layers of the models in a selected position to read and record the cartesian coordinate of each selected point. Figure 10 illustrates the measuring process.

6. Results based on statistical analysis

After completing the measures of prototyping models by 3D-digital touch probe, the models can be represented by interpolating measured data in X, Y and Z-coordinates using nearest neighbor interpolation. Figure 11 illustrates the reconstructions measured data of the prototyping models. Six meaningful pieces of statistical error have been computed mathematically in this work which are:

- Maximum distance error E_{max} .
- Average error E_{avg} .
- Normal error E_{nor} .
- Error percentage $E\%$.
- Standard deviation E_{sd} .
- Factor of similarity S_f .



Figure 10. Measuring method of the 2nd reconstructed Bezier model (prototypes model).

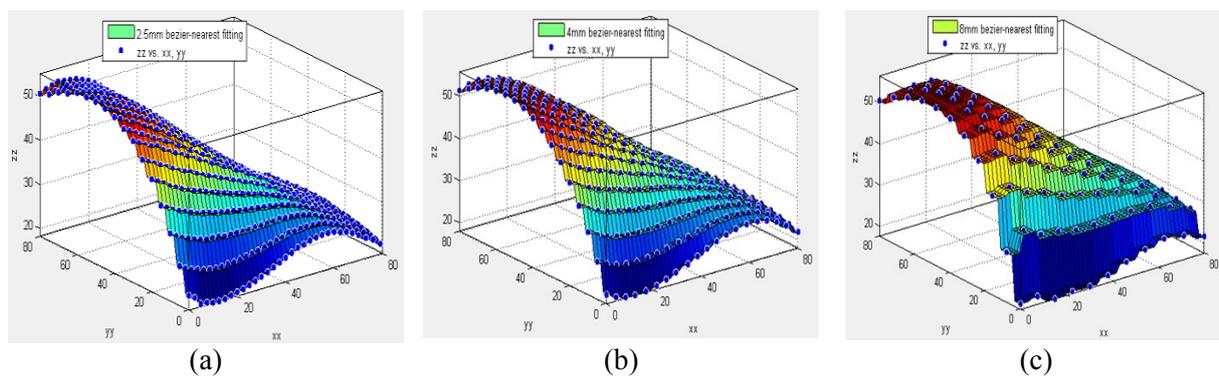


Figure 11. Reconstructed Bezier models by MATLAB: (a) 2.5 mm (b) 4 mm (c) 8mm.

6.1 Distance error

The mesh representation of the surface S can be compared to the other mesh surface S' by measuring distances $d(p_i, p_i')$ between surfaces at certain points, called samples (sample points). Sample points p_i lie on the surface S and p_i' lie on S' , where $i = 1, 2, \dots, N$; N denotes the number of samples on one surface. In our case, the surface S is called a base surface and S' is called a destination surface. Consequently, distances $d(p_i, p_i')$ represent error values between base and destination surfaces. High error values mean a significant difference between S and S' , while considerably low error values suggest S and S' to be very similar [8]. The mathematical representation of distance error calculated as:

$$d(p_i, p_i') = \sqrt{(x' - x)^2 + (y' - y)^2 + (z' - z)^2} \quad (4)$$

where: (x, y, z) represents the original data, and the (x', y', z') represents the new data constructed by interpolation processes, and because we used the same original input data (x & y) for substituted in mathematical model to reconstruct a new surface, that means [8]; $x_0 = x'$, $y_0 = y'$ and $(p_{i,i'})^2 = (z - z')^2$. For each point of a regular rectangular grid, we calculate the values of the error of elevation (E_{dis}) by using equation (5).

$$(E_{dis}) = (p_i, p_i') = (z - z') \quad (5)$$

Equation (5) represents the evaluation of error between similar surfaces.

6.2 Normal error E_{nor}

Normal error is the distance error multiple by angle error calculated as [9]:

$$N_{err} = \text{distance Error} * \cos \theta \quad (6)$$

6.3 Percentage error $E\%$

Percent error is calculated as the absolute value of the difference between the true and measured values divided by the true value multiplied by 100, calculated as [9]:

$$\%Error = \frac{\sum|true\ value - measured\ value|}{\sum|true\ value|} \times 100 \quad (7)$$

6.4 Standard deviation E_{sd}

The standard deviation is the most common measure of variability, measuring the spread of the data set and the relationship of the mean to the rest of the data. If the data points are close to the mean, indicating that the responses are fairly uniform, then the standard deviation will be small.

Conversely, if many data points are far from the mean, indicating that there is a wide variance in the responses, then the standard deviation will be large. If all the data values are equal, then the standard deviation will be zero. The standard deviation is calculated using the following formula [8]:

$$E_{sd} = \sqrt{\frac{\sum(X - \bar{X})^2}{n-1}} \quad (8)$$

where: Σ = Sum of, X = Individual score, \bar{X} = Mean of all scores, n = Sample size (number of scores).

6.5 The similarity factor (S_f)

The similarity factor (S_f) is a logarithmic transformation of the sum-squared error of differences between a new curve or surface and the reference curve or surface over all points (error), the similarity factor (S_f) is given by [9]:

$$S_f = 50 \times \text{Log}_{10} \left\{ \left[1 + \frac{1}{n} \sum_{t=1}^n (R_t - T_t)^2 \right]^{-0.5} \times 100 \right\} \quad (9)$$

where: Log_{10} = logarithm to base 10, n = number of sampling time points, Σ = summation over all time points, R_t and T_t are the reference and test dissolution values at time point (t).

7. Discussion

The results are shown in Tables 2 according to the proposed work algorithm as illustrates in Figure 12. The error analysis showed that the results obtained by the three models were significantly different because of the factor of the similarity. It can be seen clearly that the factor of similarity increased for all the models as the models reconstructed with thinner layers and it reached to about 85% for the first model reconstructed with 2.5 mm layer thickness. While the time spent for cutting the layers 2.5mm was also increased compared with the same model that reconstructed with layers of 4mm and 8mm thickness as power of machine constant in the process. So, with the proposed method in this work it is clearly seen that the reconstructed models with thinner layers increased the final accuracy of the model, but the cutting time is increased and vice versa. The cutting time in the proposed work shows that the time difference for cutting 2.5, 4 and 8mm models is not much different because cutting of 8mm thickness layers needed to decrease the nozzle speed of machine to enable laser beam penetrates this depth of thickness and this increased the cutting time although the number of layers was less. While cutting 2.5mm layers increased the nozzle speed of machine for its ability to penetrate the thickness more easily compared with 4 and 8 mm layers thickness. The number of layers is large which increases the cutting time of thinner layers significantly. The same condition applies to 4mm layer thickness.

8. Conclusion

The proposed algorithm illustrated in Figure 12 can efficiently be produced and reconstructed the 3D surfaces with acceptable accuracy and building time. Where the direct slicing of CAD model is an effective method in the proposed work field and avoiding the needs for intermediate STL file tessellation error for 3D surface and consuming the time and capacity storage for it. Where the mathematical definition of 3D CAD model play an effective role in the direct slicing procedure in CAD environment. Also, the statistical tool factor of similarity using in this work gives good impression around the similarity between CAD models and the prototype models as (84.317%) for 2.5 mm Bezier model, (72.492%) for 4mm Bezier model, (61.012%) for 8mm Bezier model produced by CNC laser cutting machine with different consuming building time.

Table 2. Statistical results of Bezier reconstructed surfaces 2.5, 4 and 8mm layers thickness.

3D Surfaces	Maximum of distance error (E_{max}) mm	Maximum of normal error (E_{nor}) mm	average of error (E_{avg}) mm	Standard deviation (E_{sd}) mm	Average error percentage ($E\%$)	Factor of similarity ($S_f\%$)
2.5mm surface	1.146	1.272	0.573	0.277	1.573	84.317
4mm surface	2.355	2.640	0.910	0.536	2.05	72.492
8mm surface	5.069	6.519	2.922	1.308	8.163	61.012

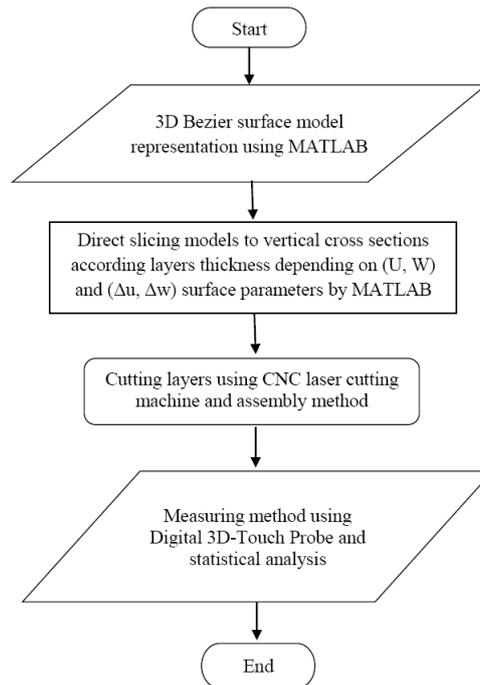


Figure 12. Flow chart of the experimental works algorithm.

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