



Sculptured Surface Design and Implementation by Lofting Design Method Using Cross-sectional B-Spline Curves

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Abstract

This research presents a particular designing strategy for a free form of surfaces, constructed by the lofting design method. The regarded surfaces were created by sliding a B-spline curves (profile curves), in addition to describing an automatic procedure for selective identification of sampling points in reverse engineering applications using Coordinate Measurement Machine. Two models have been implemented from (Ureol material) to represent the different cases of B-spline types to clarify its scope of application. The interior data of the desired surfaces was designed by MATLAB software, which then were transformed to UG-NX9 software for connecting the sections that were designed in MATLAB program and obtaining G-code programs for the models. In addition, a virtual machining process was simulated to show the machining pitfalls, using VERICUT software. The samples were machined using 3-axis vertical CNC machine (Isel) type.

Finally, the samples were measured using Faro arm (CMM inspection) and it was found that the average of errors was equal to (0.0589 mm) for the cross-sectional uniform B-spline model, and (0.1337 mm) for the lofted non-uniform B-spline model. It can be concluded that the whole steps task which built in the present research can be programmed in a single block of the part program where any surface at minimum designing time can be created from it.

Keywords: B-spline, CMM, , Lofted method, Sculptured Surface.

1. Introduction

The impact of globalization on business has forced most industries to become more innovative and implement newer strategies. In the aerospace automobiles, and many industry appliances, and different practical purposes sculptured surfaces are pertaining with designers and engineers to perform the required representation of the products. The milling of such complicated topologies is a main issue in CAM since the availability of NC machining, by their programs, to linear and circular movements [1,2]. Also, from reverse engineering which is a method utilized in the planning stage for a new products, can be depending on it to improve the design of any

surfaces or it can be create a new surfaces depending on the original surface. Lofting is a modeling technique that fits a surface through a series of curves and builds the required topology for the resulting surface. Lofting can be used to create closed bodies as well as the open bodies [3]. The lofted surface is a two-parameter parametric function $S(u, v)$; the curves provide the u parameter of the surface and the lofting algorithm defines the v parameter [4]

The researchers' studies present a various methods in reverse engineering. Many of these studies are depend on the analyzing of points cloud gained by coordinates measuring equipment, like (CMM) Coordinates Measuring Machine, Optical Scanner or interferometry

system. One of them was H. Park (2004) who introduced a novel method to fix the issue of interpolation the B-Spline surfaces to set of contours, by varying the numbers of points from contour to another. his method implies a new manner of obtaining a serial of coincident B-spline curves from the obtained contours. The method is depend on universal parameterization, that allows the knots to be taken freely but that gives the B-spline curve interpolation more linear system stability. Since the numbers of control point in the coincident B-spline curves equals to the largest numbers of contour point [5]. Ken Yano and Koichi Harada (2010) gave a new approach by skinning the generated cylindrical meshes for reconstructing B-spline surfaces. Their approach is usable only for generalizing cylindrical meshes, and there are numerous real objects which can be reconstructed and modeled by skinning the cylindrical meshes [6]. This research presents a particular designing strategy for a free form of surfaces, constructed by the lofting design method created by sliding B-spline curves.

2. B-Spline Curves Modeling and Constructing

A B-Spline curve differs from other modeling techniques such as Bezier or Hermite curve, where it generally consisting of more than one segment made up the curve. The segments are affected by only a few control points, which are the coefficient of B-Spline basis function polynomials. The curve degree is independent of the total number of control points. These characteristics allow changes in shape that do not propagate beyond one or only few local segments. The main formula that represents B-Spline curve in term of their blending functions is [7]:

$$(1)... \quad P(u) = \sum_{i=0}^n P_i N_{i,k}(u)$$

Where (Pi) is the control points and (Ni, k) representing the appropriate basis function for B-Spline representation.

For B-Spline curves, the variable (k) controls the degree of basis polynomial, which is independent of the numbers of control points. The basis function (Ni, k) is defined by following recursive equation [7]:

$$N_{i,1}(u) = 1 \quad \text{if } t_i \leq u \leq t_{i+1} \quad \dots(2)$$

$$= 0 \quad \text{otherwise}$$

And:

$$N_{i,k} = \frac{(u-t_i)N_{i,k-1}(u)}{t_{i+k-1}-t_i} + \frac{(t_{i+k}-u)N_{i+1,k-1}(u)}{t_{i+k}-t_{i+1}} \dots (3)$$

The (ti) represents the knot values, and a set of knot values comprises a knot vector (T). The knot vector has a significant influence on the blending function Ni, k (t) and theory on the B-Spline curve itself.

Since the knot vector values effecting on B-spline shapes, that classified B-Spline curves into periodic and non-periodic B-Spline curves [8].

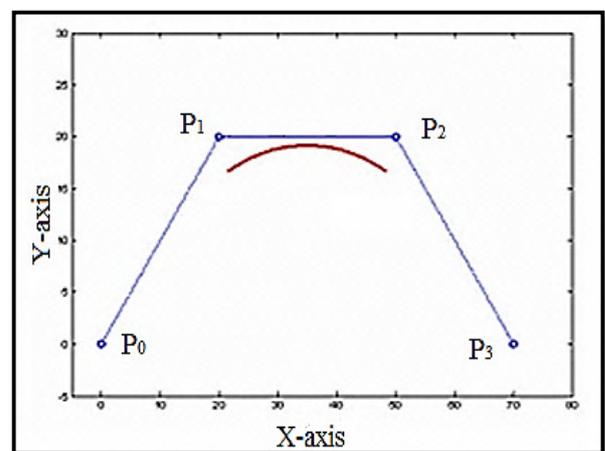
2.1. Uniform B-spline Curves

Many geometric modeling situations do not require the curve to pass through the end points. The uniform B-Spline curves is a piecewise polynomial curves controlled by a serial of points which the curves usually doesn't interpolates the end points. This method produces with a uniform or periodic knot vector, the basis functions repeating itself through successively interval for the parametric variables. The final equation of cubic periodic (uniform) B-spline curve when k4 is [9]:

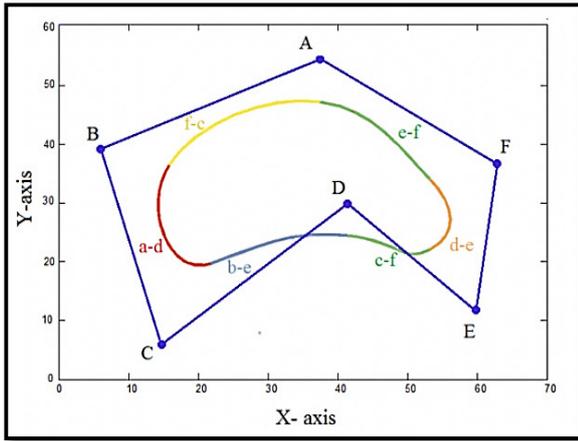
$$P(u) = U * MB * P \quad \dots(4)$$

$$P(u) = \frac{1}{6} [u^3 \quad u^2 \quad u \quad 1] \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix} \begin{bmatrix} p_0 \\ p_1 \\ p_2 \\ p_3 \end{bmatrix} \quad \dots(5)$$

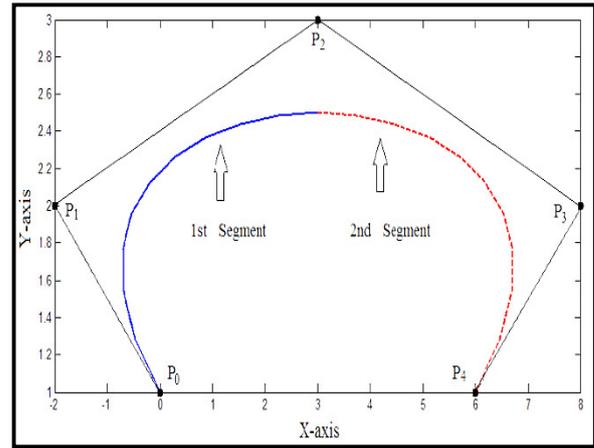
The initial data generated the required curves; the proposed programs represent the curves in a graphically with the help of MATLAB programming system. Figure (1) illustrates the designing of a single and series cubic B-Spline curves blended with each other to build the entire section of the closed B-spline curves.



(a)



(b)



(a)

Fig. 1. Construction of uniform cubic curves: (a) single curve, (b) series of curves.

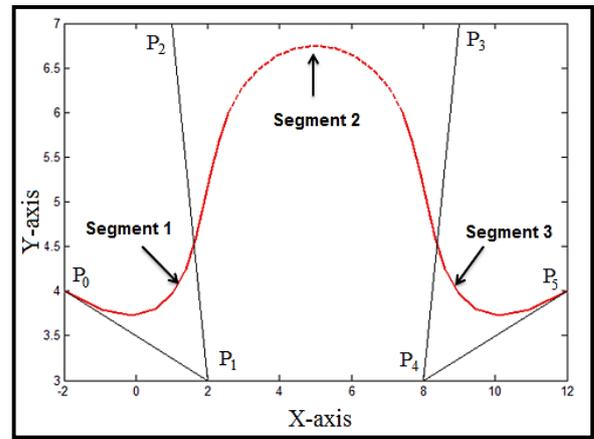
2.1 Non-Uniform B-spline Curves

Non uniform B-spline curve solves the problem of interpolating the curve with the vertices of control points, making it the preferred method in design, especially for the open parts where the uniform B-spline shows a deficiency in representation. The non-uniform B-spline curve consisting of number of segments depends on the value of the (n) and (k) variables in both directions of the vectors (u, w). For a non-uniform B-Spline curve that interpolates the end points, the (ti) in eq. (3) is [10]:

$$\left. \begin{aligned} t_i &= 0 && \text{if } i < k \\ t_i &= i - k + 1 && \text{if } k \leq i \leq n \\ t_i &= n - k + 2 && \text{if } i > n \end{aligned} \right\} \dots(6)$$

As a result of compensation the variables in eq.(3) The basis functions that generate multiple segments, each one is different from the other but complement each other.

For example the curve has two segments with (n=4, k=4), and it has three segments with (n=5, k=4). Figure (2) illustrates these cases of Non-uniform B-Spline curve.



(b)

Fig. 2. Non uniform B-Spline curves, (a) (n=4, k=4), (b) (n=5, k=4)

3. Create the Sections of B-Spline Curves in The Proposed Work

The lofting technique that used in the present work have been produced using the method of cross-sectional design concept. The models are generated through fits a surface through a series of curves and build the required topology for the resulting surface.

Two models have been designed to represent the different cases of B-spline types to clarify its scope of application. The first one created for representing the closed bodies using the Uniform B-spline curves and the reason of that is the other type of B-spline curve (non-uniform) leads to generate a state of discontinuity at meeting the first and last points of polygon of control points, that's making the uniform B-spline curves as the preferred type for modeling such kinds of closed bodies.

On the other hand the second model have been designed to representing the open bodies modeling using the Non-uniform B-spline curves because of the uniform type doesn't interpolate the end points of the control polygon which made a limitations in representation such surfaces like open profiles.

Generally both of the models had two-parameter parametric function $S(u, v)$; the curves provide the u parameter of the surface and the lofting algorithm defines the v parameter. Using the programming language in Matlab program, curves are designed of different types of B-spline curves by building algorithms including the basis functions matrices for each type as illustrated in figure (3).

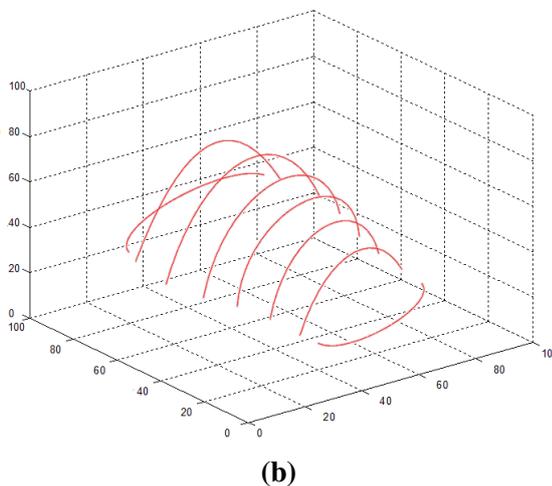
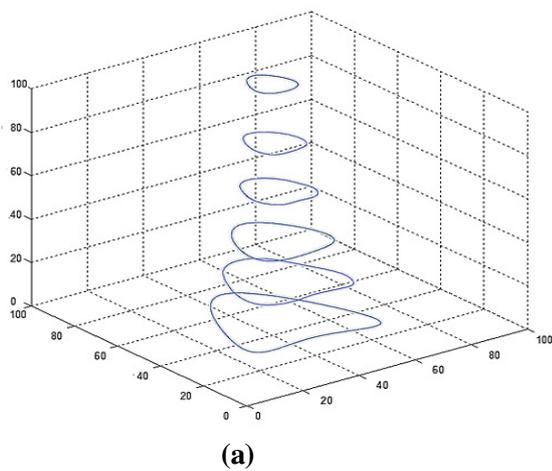


Fig. 3. The proposed sectional curves, (a) Closed uniform B-spline curves, (b) Open non-uniform B-spline curves

There are no any embedded functions in this software dedicated for the construction of the B-spline curves. Accordingly, special sub-routines have been implemented to construct the B-spline curves. Implementing the program to build the B-

spline surface needs drawing the block diagram which is shown in figure (4).

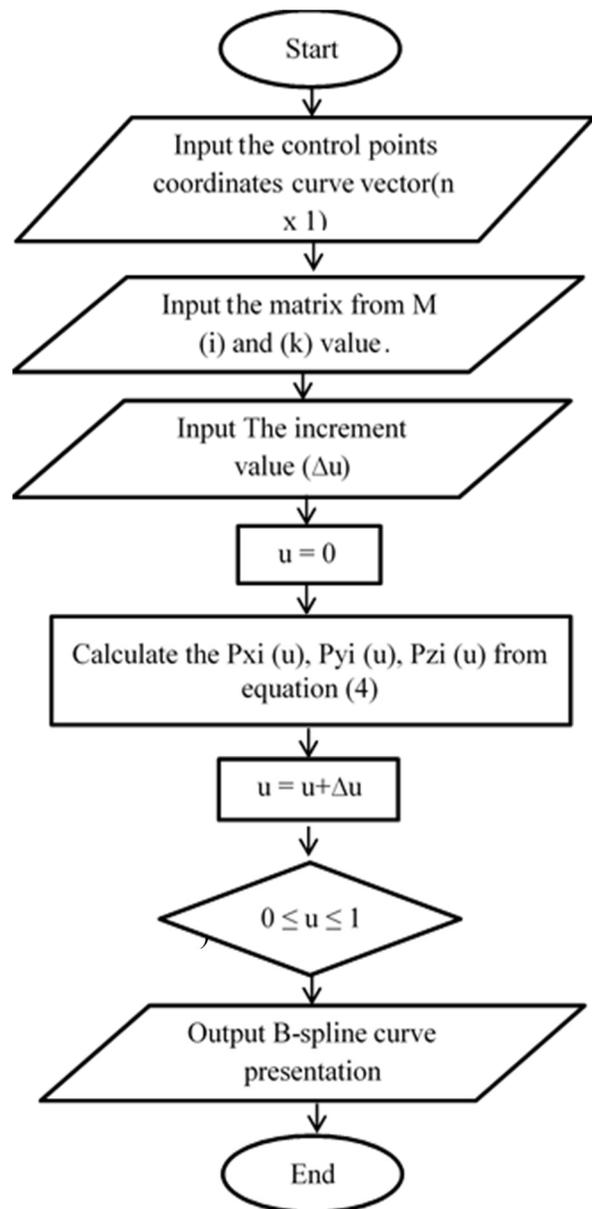


Fig. 4. Flowchart of the proposed program for building B-spline curve

4. Skinning the sectional Curves and generating tool paths for the models

The CAD module, where profile of the curves generating the surfaces which are modeled-using MATLAB, transferred to the UGS-NX9-through TXT data-exchanges file to view the required shape. After the construction of the B-spline curves, the data of each curve has been represented and saved in a single matrix of $(n \times 3)$, where n is the number of rows which is equal to $n = 1 + \frac{1}{\Delta u}$, where Δu is the increment of the

independent parameter. Each matrix is saved as (txt) file and exported to the UG-NX program. Each imported curve has been opened individually in the UG-NX program. After importing each curve, a skinning procedure is to be followed converting these curves to a surface using the following steps.

Insert surface → Mesh surface → Through curves

Figure (5) illustrates the importing CAD data to UG-NX9 software after skinning the sectional curves for the both models.

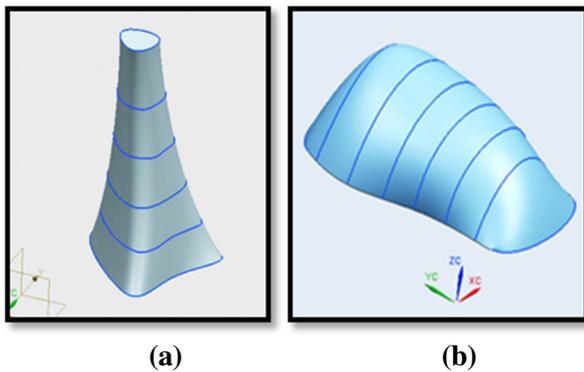


Fig. 5. Lofted surfaces after skinning, (a) Closed curves model (section of bone profile), (b) Open curves model (mouse profile).

4.1 Tool Path Generation and Simulation Utilizing UG-NX

After the completion of representing CAD models, it is followed by the process of generating the tool paths for designed part using UG-NX software. basing on the two phases of the process, the first phase is creating tool paths for the rough milling, where the characteristics must be chosen for this kind of machining, such as (Machining method, path strategies, tool shapes, tool diameters, feed rates ...etc.). The second phase is creating tool path for finish machining. In order to generate tool path for the models, flat-end tool with diameter (8mm) have been used for rough machining. Since the aim of roughing is removing massy amounts of material, the value of step over in this stage will be higher than its value in finishing, which is approximately equal to five times of finishing step over value.

Figure (6) shows the two processes of machining for first model of the closed B-spline curves (section of bone profile), in addition to the second model that represents the lofted surface of

open Non-uniform B-spline curves (mouse profile).

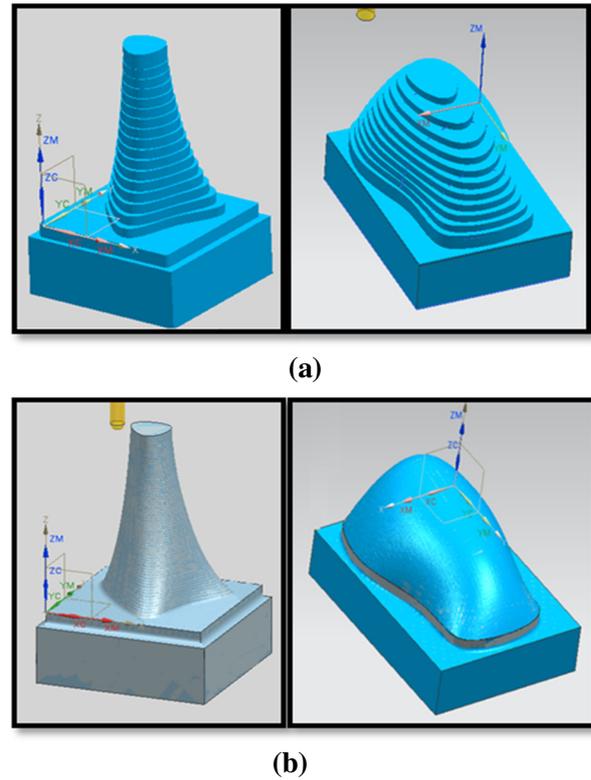


Fig. 6. Simulation of verifying tool path for the two models, (a) Rough machining, (b) Finishing process.

4.2 Tool Path Verification

The verification process has been done for the generated tool path using VERICUT software to detect the errors of NC program before loading the program on the CNC machine. G-code files imported to VERICUT software and a virtual machine has been designed to verify the tool path, and checking the machining pitfalls, as shown in figure (7).

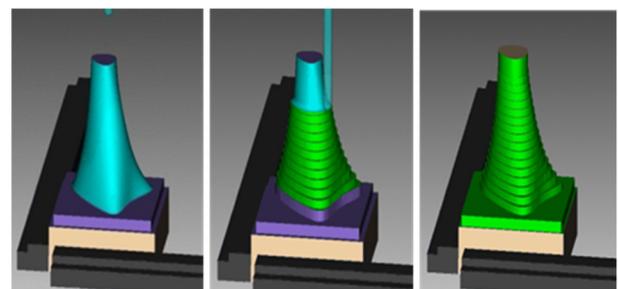


Fig. 7. Progress simulation of machining using VERICUT software

5. Experimental Work

The machining process has been conducted on models from Ureol material, with different dimensions of the primary blocks as follows:-

1. Closed lofted model (uniform B-spline curves):
x= 50 mm, y= 50 mm, z= 75 mm
2. Open lofted model (Non-uniform B-spline curves): x= 80 mm, y= 100 mm, z= 80 mm.

5.1 CNC Milling Machine

Milling processes have been performed on a vertical 3-axis CNC Milling machine "ISEL type" in the institute for machine elements, design and manufacturing in TU Bergakademie Freiberg in Germany, as illustrated in Figure (8). The characteristics are given in Table (1), to achieve the milling process for the models that have been designed.



Fig. 8. 3-axis CNC machine (Isel type)

Table 1,
Characteristics of CNC milling machine

Features of CNC milling machine ICP 4030	
Traverse path X/Y/Z [mm]	400 x 300 x 140
Software	Pro NC
Repeatability [mm]	± 0.02
Controller	500W power supply unit with processor board
Process speed X/Y/Z [mm/s]	100
Drive motors	Stepper motors
Dimensions W × D × H [mm]	780 × 850 × 810
Throughput [bit/s]	170

5.2 Machining Cutters

Two kinds of milling tool are utilized in the proposed work research:

- 1- Flat-end mill tool with (Ø 8 mm) dia. and four flute cutters, made from (HSS) high-speed steel have been utilized for roughing.
- 2- Ball-end mill tool with (Ø 8 mm) dia. made from (HSS) for finishing. Fig.(9) shows the two types of cutting tools.

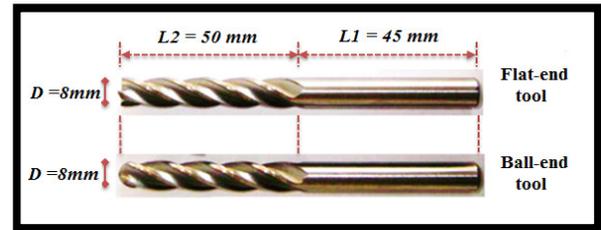


Fig. 9. Cutting tools used for machining

5.3 Surface Machining

The machining operations are executed in two processes; rough milling and finishing. Removing materials occurred in rapid way as much as possible during rough milling. The tool removed the materials in layers till the surface is encountered. Large amounts of material removal rate in rough machining are utilized to minimizing the process time. The rough milling occurred in parallel layers till access the required depths. The fineness of result surfaces in roughing is not significant as layers of material which left for finishing. Figure (10) shows the two passes roughing and finishing for machined the first part and figure (11) clarify the two phases for the second part.

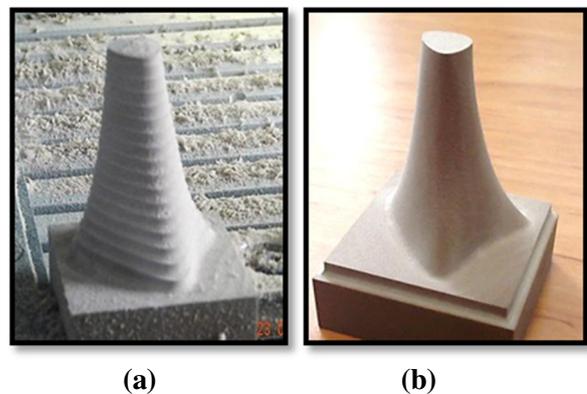


Fig. 10. Machining process for (section of bone profile), (a) Roughing, (b) Finishing

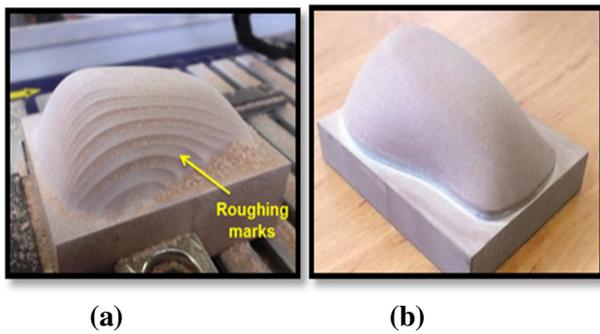


Fig. 11. Machining process for (mouse profile), (a) Roughing, (b) Finishing

6. Measurement and Inspection

The measurement process have been implemented using Faro-arm which is a portable (CMM) coordinates measuring machine that gives an easy products verifications for the manufacturers to assessment the quality by making 3D inspection, CAD comparisons, dimensional analyzing, and reverse engineering. This arm consists of 6 degrees of freedom which facilitate the measurement process. Figure (12) shows the measuring arm.

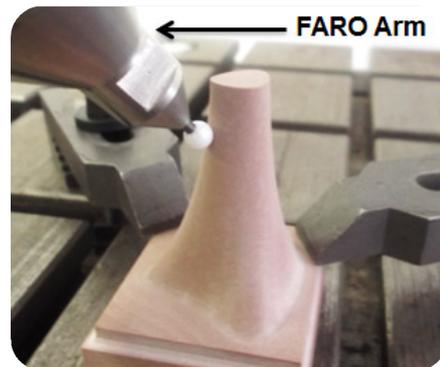


Fig. 12. Faro arm (CMM).

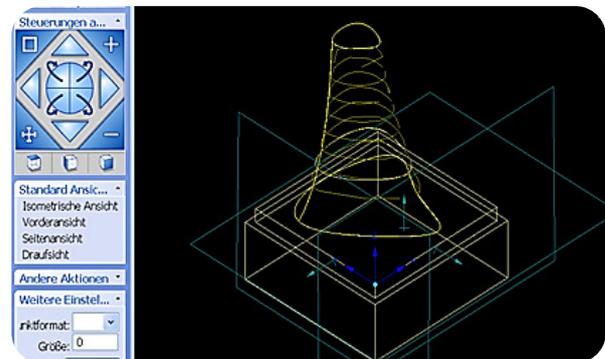
After machining, the measurement process has been conducted for the manufactured parts. The aim of testing these parts is to ensure that the product is manufactured with high precision, and to find out the differences between the CAD models which have been designed and the parts after the manufacturing process. Depending on the results of measuring, there will be evaluation of designing methods to see its feasibility success.

6.1 Measurement of the Closed Lofted surface (Section of Bone)

The measurement of each product (CAM model) can be conducted by scanning the entire products surface through passing the ball of the FARO arm over the whole surface. After measurements, the FARO CAM2 measure software imports design files in (IGES) format which contain the coordinate of each scanned points. Figure (13) illustrates the comparison process for the first model surface.



(a)



(b)

Fig. 13. Comparing between CAD and CAM models of the closed lofted surface, (a) CAD model in (FAROCAM2 software), (b) Scanning on real part.

After completion of measurement scheme, the program provides report, explains the details of the measurement and refers to the amount of error incident. Figure (2) shows a sample of measuring data for the first part.

M_FLÄCHE001-001 (Gemessen Scan über Schnittbereich)						
Übersichtsliste	27 Punkte		0 Punkte außerhalb Toleranz			
Durchschnitt :	-0000,0544	Standardabweichung :		0000,0585		
Min. Abstand :	-0000,1407	Max. Abstand :		0000,0617		
Gemessen	Sollwert	Obere Tol	Untere Tol	Abw	Außerh. Tol	
Länge	0000,1407	0000,0000	0000,1500	-0000,1500	0000,1407	***** →
Messergebnisse						
ID	X	Y	Z	Sollwert	Abstand	Außerh. Tol
1	0027,8656	0010,9075	0008,5412	N_FLÄCHE001	-0000,0116	*****
2	0027,2294	0010,5256	0008,4921	N_FLÄCHE001	0000,0151	*****
3	0026,3550	0010,2806	0008,4959	N_FLÄCHE001	0000,0284	*****
4	0029,0300	0012,0435	0008,7320	N_FLÄCHE001	-0000,0252	*****
5	0030,4609	0014,4685	0009,0419	N_FLÄCHE001	-0000,0466	*****
6	0031,6691	0017,5110	0009,2432	N_FLÄCHE001	-0000,0598	*****
7	0032,1145	0018,8331	0009,2824	N_FLÄCHE001	-0000,0602	*****
8	0032,6100	0020,3896	0009,2957	N_FLÄCHE001	-0000,0620	*****
9	0033,6295	0023,4633	0009,2178	N_FLÄCHE001	-0000,0402	*****
10	0033,9890	0024,5030	0009,1635	N_FLÄCHE001	-0000,0372	*****
11	0035,3703	0029,0248	0008,7915	N_FLÄCHE001	-0000,0439	*****
12	0035,5649	0030,2523	0008,6665	N_FLÄCHE001	-0000,0571	*****
13	0035,2942	0032,7453	0008,5097	N_FLÄCHE001	-0000,0829	*****
14	0031,5511	0035,7756	0008,9844	N_FLÄCHE001	-0000,1073	*****
15	0030,0046	0036,2854	0009,0906	N_FLÄCHE001	-0000,1169	***** ←
16	0028,6416	0036,6350	0009,1438	N_FLÄCHE001	-0000,1161	***** ←
17	0025,0529	0037,2389	0009,1979	N_FLÄCHE001	-0000,0991	*****
18	0023,9696	0037,3465	0009,2009	N_FLÄCHE001	-0000,0908	*****
19	0017,5503	0037,1503	0009,1757	N_FLÄCHE001	-0000,1364	***** ←
20	0015,7382	0036,8392	0009,1619	N_FLÄCHE001	-0000,1335	***** ←
21	0013,9018	0036,3437	0009,1436	N_FLÄCHE001	-0000,1407	***** ←
22	0011,6982	0035,4467	0009,1099	N_FLÄCHE001	-0000,1281	***** ←
23	0008,2393	0031,7991	0009,0642	N_FLÄCHE001	-0000,0447	*****
24	0008,1261	0029,2156	0009,1727	N_FLÄCHE001	-0000,0158	*****
25	0014,0628	0018,6232	0009,3463	N_FLÄCHE001	0000,0352	*****
26	0019,3629	0013,4887	0009,1617	N_FLÄCHE001	0000,0473	*****
27	0021,3444	0012,0195	0009,0183	N_FLÄCHE001	0000,0617	*****

Fig. 14. Sample of measuring data for the closed lofted part

In addition to the measuring data, it provides the values of some constants and variables such as the average of error and standard deviation.

$$\text{Average of error } (\mu) = \frac{\sum xi}{n} \dots(7)$$

$$\text{Standard deviation } (\sigma) = \sqrt{\frac{\sum(xi+\mu)^2}{n}} \dots(8)$$

Where: xi= error values, n= number of errors.

Table 2,
The average error, standard deviation and maximum error for the first model.

The average error	0.0589	mm
Standard deviation	0.0713	mm
Maximum error	0.1827	mm



Fig. 15. Comparing between CAD and CAM models of the open lofted surface.

6.2 Measurement of Open Lofted surface

Figure (15): shows the Comparison of CAD models and real part of the lofted surface, and figure (16) shows sample of measuring data for the second part (mouse profile).

M_FLÄCHE001-006 (Gemessen Scan über Schnittbereich .)					
Übersichtsliste	11 Punkte		1 Punkte außerhalb Toleranz		3.
Durchschnitt :	0000,1237		Standardabweichung :		0000,1967
Min. Abstand :	-0000,1608		Max. Abstand :		0000,3083
Gemessen	Obere Tol	Untere Tol	Abw	Außerh. Tol	
Länge	0000,3083	0000,3000	-0000,3000	0000,3083	0000,0083
Messergebnisse					
ID	X	Y	Z	Abstand	Außerh. Tol
1	0007,6754	0034,7194	0011,7774	0000,2891	*****
2	0011,5697	0034,8040	0018,2012	0000,2828	*****
3	0016,3053	0034,7722	0023,9709	0000,3083	0000,0083
4	0017,2838	0034,7530	0025,0060	0000,2765	*****
5	0018,7060	0034,7210	0026,3284	0000,2806	*****
6	0020,0835	0034,6847	0027,5486	0000,2420	*****
7	0027,8750	0034,4557	0032,4223	0000,1442	*****
8	0043,9272	0034,3395	0034,2205	-0000,0450	*****
9	0052,3716	0034,5499	0030,8793	-0000,1028	*****
10	0065,4352	0034,7866	0017,9875	-0000,1608	*****

M_FLÄCHE001-007 (Gemessen Scan über Schnittbereich .)					
Übersichtsliste	11 Punkte		0 Punkte außerhalb Toleranz		
Durchschnitt :	0000,0866		Standardabweichung :		0000,1981
Min. Abstand :	-0000,2017		Max. Abstand :		0000,2841
Gemessen	Obere Tol	Untere Tol	Abw	Außerh. Tol	
Länge	0000,2841	0000,3000	-0000,3000	0000,2841	*****
Messergebnisse					
ID	X	Y	Z	Abstand	Außerh. Tol
1	0008,0985	0039,4525	0011,4201	0000,2812	*****
2	0011,3163	0039,5907	0017,2773	0000,2841	*****
3	0015,0809	0039,6290	0022,3349	0000,2723	*****
4	0016,6800	0039,6205	0024,0660	0000,2676	*****
5	0020,5286	0039,5655	0027,4908	0000,2388	*****
6	0028,7111	0039,3977	0032,1247	0000,1227	*****
7	0035,1048	0039,3083	0033,7375	0000,0456	*****
8	0043,8557	0039,3159	0033,4566	-0000,0409	*****
9	0051,9890	0039,4431	0030,5432	-0000,1242	*****
10	0065,4872	0039,5446	0017,3170	-0000,2017	*****

Fig. 16. Sample of measuring data for the open lofted part.

The big red arrow refers to exceeding the measured error to the given value of tolerance. On the other hand, the small yellow arrow refers to approach the value of measured error to the given tolerance.

Table 3,
The average error, standard deviation and maximum error for the open lofted surface.

The average error	0.1337	mm
Standard deviation	0.0414	mm
Maximum error	0.1912	mm

7. Conclusion

- The design methodology of Lofted B-spline surface does not effect on the manufacturing result. The agreement for this concluding remark is the maximum produced error for closed B-spline model and the open lofted B-

spline model are (0.1827) mm and (0.1912) mm respectively.

- The first segment of the non-uniform B-spline surface start with the polygon of control points, however it doesn't end with it, in opposite to the last segment which is end with the polygon of control points but it doesn't start with it.
- In spite of the limitation of interpolating the uniform B-spline curve with the polygon of control polygon, however it considered an advantage for representing the closed parts, because using the non-uniform B-spline curves leads to generate a state of discontinuity at meeting the first and last points of polygon of control points. Contrarily of representing the open parts which depends on the non-uniform type.
- The method has been implemented on various types of sculptured models. Looking at the given result, it is possible to say that this method has a good level of applicability in automated scansion systems

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تصميم وتنفيذ الاسطح الحرة باستخدام طريقة التصميم للمقاطع المستعرضة لمنحنيات الـ B-spline

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خلاصة

هذا البحث يقدم استراتيجية لتصميم الاسطح بشكل عملي، تتم بوساطة استخدام طريقة المنحنيات المستعرضة. الاسطح التي تم دراستها تم تكوينها بوساطة سلسلة من الشرائح المتعاقبة المكونة للشكل. فضلا عن توصيف طريقة تعريف ونمذجة النقاط باستخدام تطبيقات الهندسة العكسية باستخدام مكائن قياس الاحداثيات. تم تنفيذ نموذجين من مادة (Ureol) لتمثيل الحالات المختلفة لمنحنيات الـ B-spline لإيضاح مجال التطبيق الملائم لها. البيانات المطلوبة تم تصميمها بوساطة برنامج الـ MATLAB ثم تم نقلها الى برنامج الـ UG-NX9 لغرض ربط المنحنيات وتكوين السطوح والحصول على برامج الـ G-code الخاصة بالنماذج. كذلك تم عمل محاكاة افتراضية باستخدام برنامج الـ VERICUT لاظهار الاخطاء المزامنة لعملية التشغيل. تم تنفيذ النماذج على ماكينة تفريز لثلاثة محاور نوع (Isel). في نهاية هذه الاجراءات تم قياس النماذج باستخدام ماكينة قياس الاحداثيات (Faro Arm CMM)، وجد ان قيمة معدل الخطأ (0.0589) لنموذج المنحنيات المستعرضة باستخدام نوع الـ B-spline المنتظم، و(0.1337) لنموذج المنحنيات المستعرضة باستخدام الـ B-spline غير المنتظم. يمكن الاستنتاج ان خطوات البرنامج المقترح التي تم بناؤها يمكن برمجتها في برنامج تصميمي واحد من هذا يمكننا تنفيذ اي سطح في أقصر وقت تصميمي.