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Comparison between T-spline surface and NURBS surface

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ABSTRACT

This research use T-spline for surface modeling and compare it with NURBS modeling to get the best modeling points between the two methods. The comparison will be through surface analysis and manufacturing process. T-Splines surfaces typically have 50-70% less geometric data structure than the equivalent NURBS surface, allowing for faster and more controlled direct editing and shape optimization. In Environment Map analysis, the image of T-Spline surface for the models is reflected more clearly than a NURBS surface, in measurement runtime for machining (roughing and finishing), the T-spline surface for the bicycle seat model is machined in (16 minutes) less than machining the NURBS surface, and the T-Spline surface for the longitudinal section of the bottle model is machined in (10 minutes) less than machining the NURBS surface. In measurement of roughness, the T-Spline surface for the bicycle seat model has (2.4861 µm) average (Ra) for patches measured roughness average (Ra), and the NURBS surface has (4.9216 µm) average (Ra) for patches measured roughness average (Ra).

Keywords: T-Spline, NURBS

مقارنة بين سطح الـ T-spline وسطح الـ NURBS

الخلاصة

في هذا البحث تم استخدام T-SPLINE للنمذجة السطحية لمقارنتها مع النمذجة السطحية للـ NURBS للحصول على أفضل نقاط النمذجة بين الطريقتين. وسوف تكون المقارنة من خلال تحليل السطح وعملية التصنيع. أن أسطح T-SPLINE عادة ما تكون بيانات الهيكل الهندسي أقل في (50-70٪) من السطح المعادل للـ NURBS، وفي قياس وقت التشغيل، سطح الـ T-SPLINE لنموذج مقعد الدراجة شغل في وقت أقل بمقدار (16 دقيقة) من تشغيل سطح الـ NURBS، وسطح الـ T-SPLINE للمقطع الطولي من نموذج الزجاجة شغل في وقت أقل بمقدار (١٠ دقائق) من تشغيل سطح الـ NURBS وفي قياس الخشونة، سطح الـ T-SPLINE لنموذج مقعد

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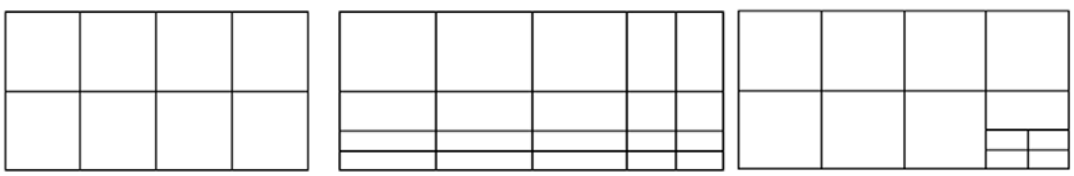
الدراجة يمتلك (2,4861 ميكرون) وهو معدل (Ra) للبقع التي تم قياس معدل متوسط الخشونة لها، وسطح الـ NURBS يمتلك (4,9216 ميكرون) وهو معدل (Ra) للبقع التي تم قياس معدل متوسط الخشونة لها.

INTRODUCTION

T-spline was first introduced by Sederberg et al. 2003 [1] as a generalization of NURBS (non-uniform rational B-splines), and has recently also been introduced in an analysis setting [2, 3]. As opposed to B-splines and NURBS, T-splines are not restricted to a tensor product structure. That is,

while NURBS control points must lie in a rectangular grid, T-splines may form an incomplete grid, with T-junctions. The tensor product structure of NURBS implicates that a local refinement is impossible, since complete rows and columns must be inserted in the control point grid, which will create unwanted degrees of freedom elsewhere in the analysed problem, as shown in Figure Figure (1). Since this is avoided with T-splines, they are superior to NURBS when it comes to local refinement.

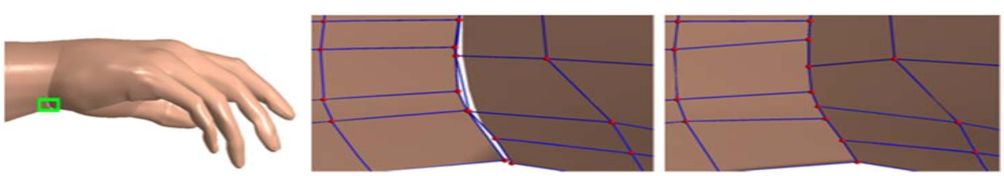


(a) No refinement **(b) Tensor product refinement with NURBS** **(c) Local refinement with T-splines**

Figure (1): Tensor product refinement vs. local refinement [1]

Local refinement has many benefits. For the same geometric representation, T-splines give fewer control points compared to NURBS, implying lower computational cost when performing analyses. An analysis cannot be performed on a model containing gaps, which are often non-avoidable in a NURBS model, because closing a gap requires refinement of the whole model. The refinement process increases the number of control points drastically and is therefore usually not performed. In contrast to this, using T-spline control net, the gaps may be locally refined, keeping the number of control points low while still giving an analysis-suitable model. Local refinement of gaps is often referred to as T-spline merging and an example to this is shown in Figure(2) [4].

T-splines were invented by Thomas W. Sederberg in 2003. In 2007 the U.S. Patent Office granted him patent number 7,274,364. The acquisition of T-spline technology by Autodesk in 2011 suggests that this technology is important for the CAD industry.



(a) Hand modeled with NURBS surfaces **(b) NURBS control grids of highlighted Region** **(c) T-spline control grid**

Figure (2): Gap closed using T-spline merging [4]

The proposed system for designing, manufacturing and analysis of T-spline surface and compares to NURBS surface.

First (CAD Module), design is of two types of models convex model (bicycle seat) and concave model (longitudinal section of the bottle) for each T-spline surface and NURBS surface using Rhinoceros 5.0 software.

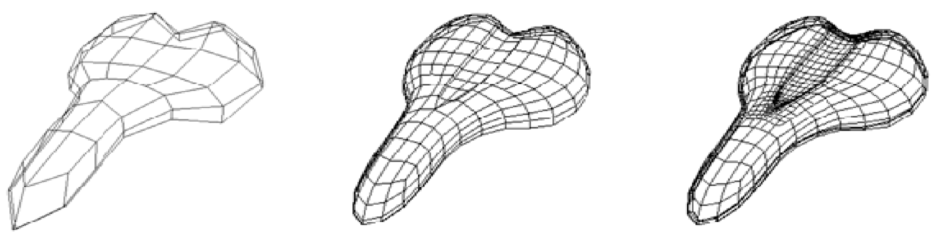
Second (CAM Module), the results of Rhinoceros 5.0 software are fed automatically to the UG-NX8.5 software to generate the coded instructions.

Third (Surface Machining), the results of UG-NX8.5 software are fed automatically to CNC Milling Machine to machine the constructed surfaces.

Fourth (Analyses), analysis is carried out of surfaces and measure the roughness and curvature.

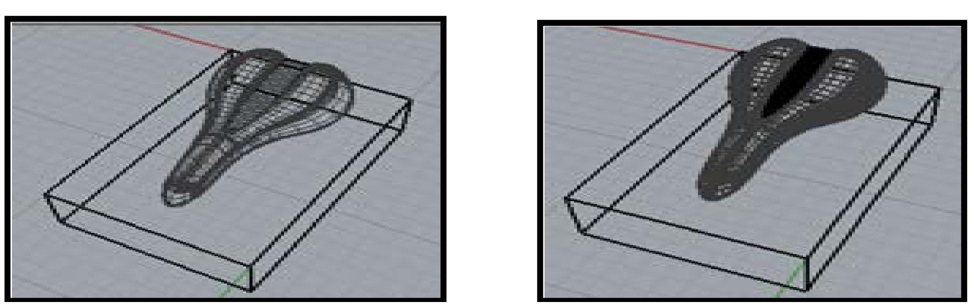
CAD Module (Computer Aided Design)

In this module two types of models, convex model (bicycle seat) and concave model (longitudinal section of the bottle) are designed for each T-spline surface and NURBS surface using Rhinoceros 5.0 software. When the first model (bicycle seat) starts off by creating some layers Figure (3), the first layer is designed, it for Low Detail, second layer for Medium Detail, third layer for High Detail and fourth layer for complete T-spline Surface (bicycle seat) and makes copy and converts this copy to NURBS Surface by "tsConvertToRhinosurf" command.



(a) (b) (c)

(a) First layer for Low Detail. (b) Second layer for Medium Detail.
(c) Third layer for High Detail.
Figure (3): layers for design bicycle seat model



(a)T-spline surface **(b) NURBS surface**

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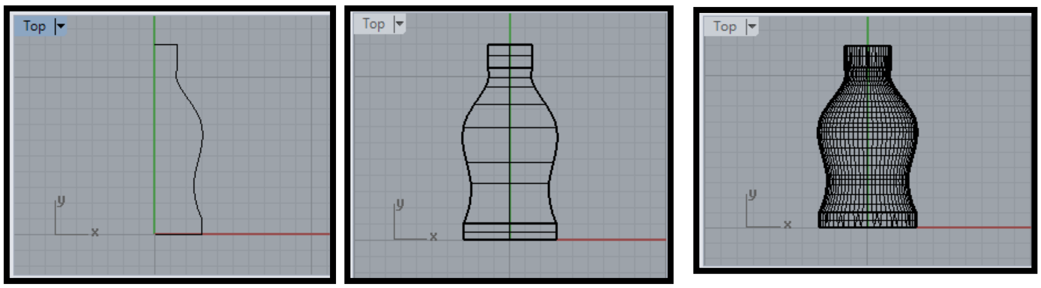
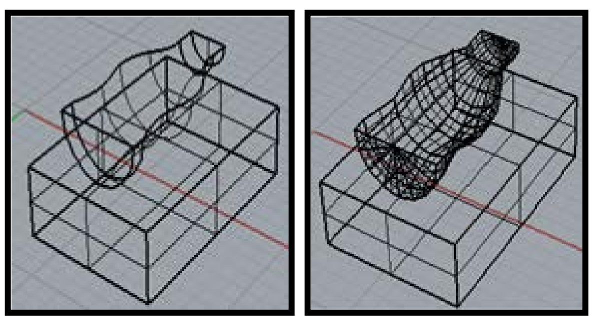
Figure (4): bicycle seat model

The second model is longitudinal section of the bottle; this model was designed by drawing lines by using "Polyline" Command and "control points curve" Command, revolving 180 degree around the Y axis by "Revolve" command, It gives the surface thickness of 3 mm by "tsThicken" command, and after that converts the drawing to mesh by " mesh " command as shown in Figure (5) and makes two copies first copy converts mesh to T-spline by " tsConvert " command and second copy converts mesh to NURBS by " mesh to nurbs " command.



(a) Lines (b) Revolve around the Y axis (c) Mesh

Figure (5): Stages for design of longitudinal section of the bottle model



(a) T-spline surface (b) NURBS surface

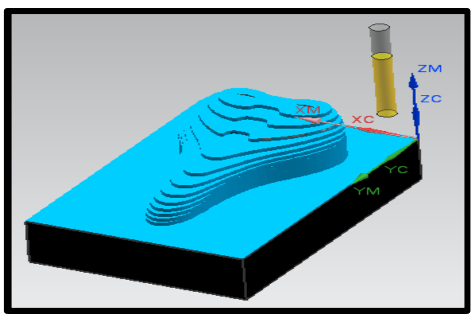
Figure (6): longitudinal section of the bottle model

CAM Module (Computer Aided Manufacturing)

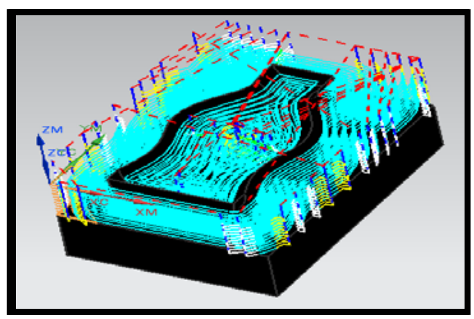
After the completion of representing CAD models, process of generating the tool paths for designed part follows. The tool path status control in NX CAM is an extremely useful tool in a programming technology. The CAD data is converted to CAM data through the CAM module utilizing the post processors of UG- NX8.5 software after defining the controller type of CNC machine. The software provides machining environment. Many procedures must be taken before creating an actual tool path, since there are two phases of the operation, the first phase is creating tool path for rough machining, where settings should be selected for this type, such as (method of machining, tool geometry, tool diameter, feed rate .etc.). The second phase is creating tool path for finish machining.

Through setting mill-contour method with rough machining by cavity mill type, the cutting takes the form of layers, flat-end tool with (8mm) in diameter has been selected for roughing phase and through setting mill-contour method with finish machining by contour area type, ball-end tool with (8mm) in diameter has been selected for finishing phase.

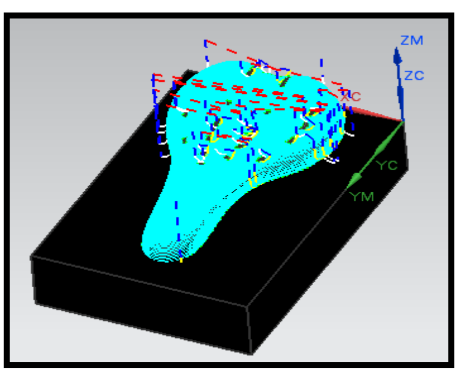
At the same time it is possible to apply different strategies of generating the tool path such as (Zig-zag tool path, spiral, follow part …etc.) , follow part tool path was chosen for roughing T-spline surface and NURBS surface for bicycle seat model and longitudinal section of the bottle model , Zig-zag tool path was chosen for finishing T-spline surface and NURBS surface for bicycle seat model , and follow periphery tool path was chosen for finishing T-spline surface and NURBS surface for longitudinal section of the bottle model. After identifying machining parameters and selecting the required type of tool path for rough and finish machining, the software provides a simulation process to clarify the operations. After completion of creating a program for each process, G-code files are obtained for both operations using the post processing of the program after specifying the number of axis of the required machine, where the program will provide a text file explaining the operational movements of the machine that consists of G-codes and machining parameters, which are regarded as the readable language of the machine. Figure (7) show examples of tool path generation and simulation.



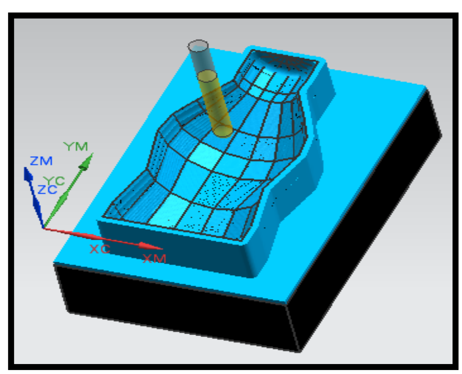
(a) Simulation of roughing (T-spline)



(b) Tool path for roughing (T-spline)



(c) Tool path for finishing (NURBS)



(d) Simulation of finishing (NURBS)

Figure (7): examples of tool path generation and simulation

Surface Machining

Milling processes have been performed on a vertical 3-axis CNC Milling machine "C-tek" type in Turning Unit, Training Center and Laboratories at the University of Technology. The machining process has been conducted on models from Polytetrafluoroethylene material (Teflon), with dimensions of the primary blocks as follows: length 100 mm, width 150 mm and height 70 mm. Two types of cutting tool are used in this research:

1-Flat-end mill tool with diameter = (Ø 8 mm) made from high-speed steel HSS with four flute cutters has been used for rough machining.

2-Ball-end mill tool with diameter = (Ø 8 mm) made from HSS with three flute cutters was used for finishing operation.

The milling is done in two phases roughing and finishing. Material is removed as rapidly as possible in roughing. The cutter removes material in layers until the surface is encountered. During roughing, high metal removal rates are used to minimize the processing times. The roughing is mostly done in parallel layers until a certain depth. During finishing, the final layers of material will be removed to obtain surfaces within an appropriate geometrical accuracy and higher surface quality. Table (1) shows the machining characteristics for both roughing and finishing phases for the bicycle seat models (T-spline and NURBS models) and Table (2) shows the machining characteristics of both roughing and finishing phases for longitudinal section of the bottle models (T-spline and NURBS models). Figure (8) show the bicycle seat models and longitudinal section of the bottle models after finishing.

Table (1): Machining characteristics of machining the bicycle seat models

	Cutter Type	Cutter diameter	Side step	Feed rate	spindle Speed
Roughing process	Flat-end cutter	Ø 8 mm	3 mm	2000 mm/min	1000 rpm
Finishing process	Ball-end cutter	Ø 8 mm	0.4 mm	200 mm/min	2500 rpm

Table (2): Machining characteristics of machining the bottle models

	Cutter Type	Cutter diameter	Side step	Feed rate	spindle Speed
Roughing process	Flat-end cutter	Ø 8 mm	3 mm	1000 mm/min	1000 rpm
Finishing process	Ball-end cutter	Ø 8 mm	0.4 mm	500 mm/min	2000 rpm

(a) T-spline surface (bicycle seat)

(b) NURBS surface (bicycle seat)

(c) T-spline surface (bottle)

(d) NURBS surface (bottle)

Figure (8): the bicycle seat models and the bottle models after finishing.

Runtime for Roughing and Finishing Process

Runtime was calculated for roughing and finishing process in CNC milling machine by timer for models.

Table (3): Runtime for machining the bicycle seat models

	T-spline surface	NURBS surface
Roughing process	00:29:21 (Hours: minutes: seconds)	00:32:30 (Hours: minutes: seconds)
Finishing process	00:46:22 (Hours: minutes: seconds)	00:59:27 (Hours: minutes: seconds)

Table (4): Runtime for machining the bottle models

	T-spline surface	NURBS surface
Roughing process	00:50:34 (Hours: minutes: seconds)	00:53:57 (Hours: minutes: seconds)
Finishing process	00:12:40 (Hours: minutes: seconds)	00:18:03 (Hours: minutes: seconds)

Analyses

Data Structure Analysis

This analysis presents reports on detailed technical information about the geometric data structure of the Models. This analysis is done by "List" command in Rhinoceros 5.0 software.Table (5) shows the geometric data structure for the bicycle seat models (T-spline and NURBS models) and Table (6) shows the geometric data structure for longitudinal section of the bottle models (T-spline and NURBS models).

Table (5): The geometric data structure for the bicycle seat models

Analyze	NURBS Surface	T-spline Surface
surfaces	6586	3293
3d curve	13380	7042
2d curves	26344	13172
vertices	12753	7085
edges	13380	7042
trims	26344	13172
loops	6586	3293
faces	6586	3293

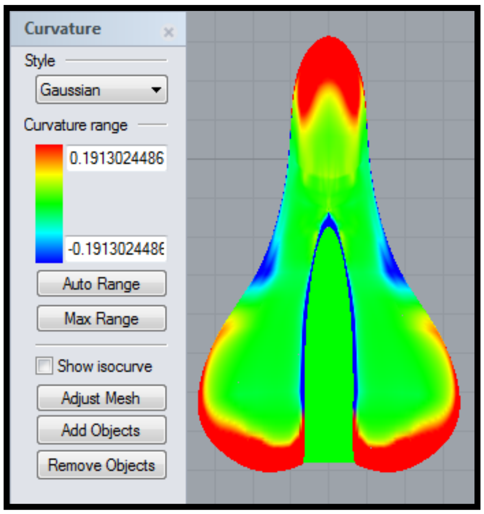
Table (6): The geometric data structure for the bottle models

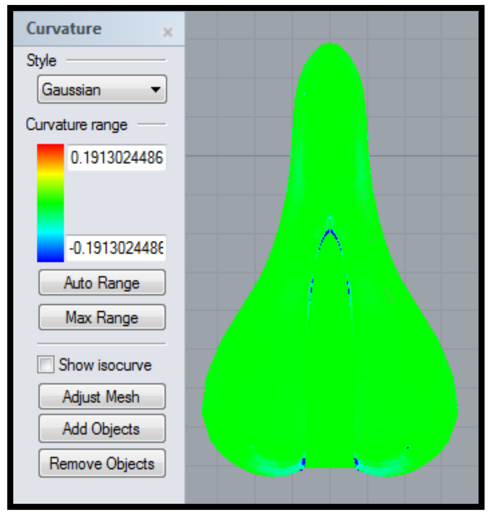
Analyze	NURBS Surface	T-spline Surface
surfaces	368	16
3d curve	746	50
2d curves	1472	64
vertices	393	115
edges	746	50
trims	1472	64
loops	368	16
faces	368	16

Gaussian Curvature Analysis

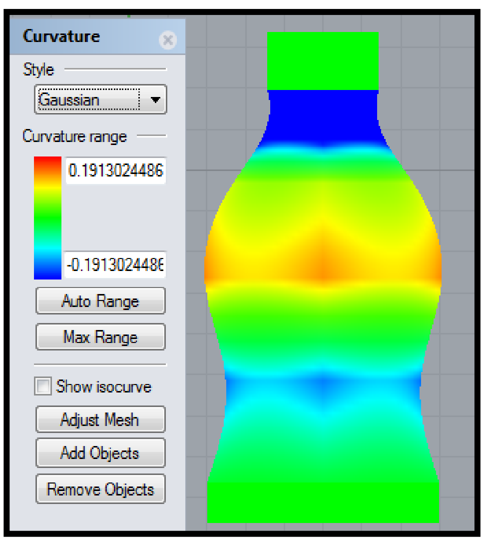
The Gaussian curvature is the product of the two principal curvatures $K = \kappa 1 \ \kappa 2$. This analysis is done by "Curvature Analysis" command in Rhinoceros 5.0 software. Figure (9) shows Gaussian curvature analysis for the bicycle seat models and longitudinal section of the bottle models. The sign of the Gaussian curvature can be used to characterize the surface.

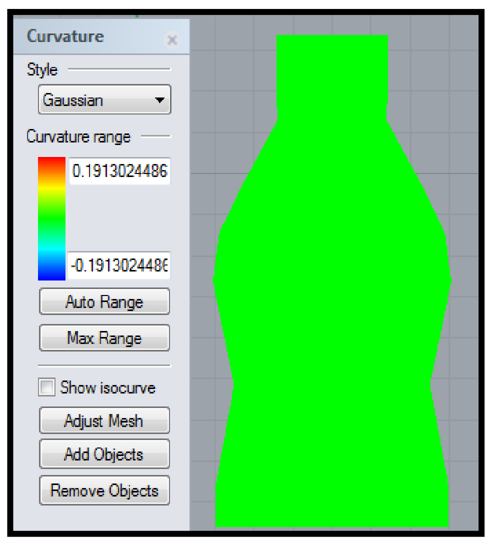
- If both principal curvatures are the same, sign: $\kappa 1 \kappa 2 > 0$, then the Gaussian curvature is positive and the surface is said to have an elliptic point.
- If the principal curvatures have different signs: $\kappa 1 \kappa 2 < 0$, then the Gaussian curvature is negative and the surface is said to have a hyperbolic point.
- If one of the principal curvature is zero: $\kappa 1 \kappa 2 = 0$, the Gaussian curvature is zero and the surface is said to have a parabolic point. [5]





(a) T-spline surface (bicycle seat) **(b) NURBS surface (bicycle seat)**





(c) T-spline surface (bottle) **(d) NURBS surface (bottle)**

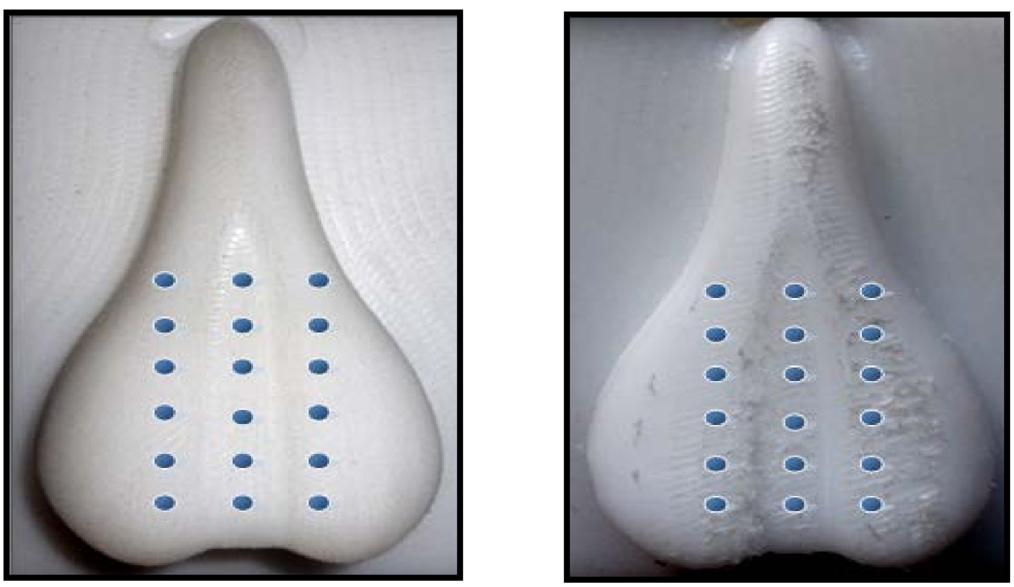
Figure (9): Gaussian curvature analysis for the bicycle seat models and

longitudinal section of the bottle models.

Measurement of Roughness by Pocket Surf

A set of points on the surface of the bicycle seat models (T-spline and NURBS) have been taken to form patches to measure roughness average (Ra) of these points by Pocket Surf equipment available in Measurements Laboratory in Department of Production and Metallurgy Engineering in University of Technology. Roughness average (Ra) is the arithmetic average of the absolute values of the roughness profile ordinates.

Gaussian curvature was measured for these points by "Curvature Analysis" command in Rhinoceros 5.0 software for the bicycle seat models (T-spline and NURBS). Figure (10) shows points that were measured for roughness and Gaussian curvature for the bicycle seat models. Table (7) shows the values of roughness and of Gaussian curvature for the T-spline bicycle seat model and Table (8) shows the values of roughness and of Gaussian curvature for the NURBS bicycle seat model. These patches have been mapped by MATLAB software to draw the coordinates of the points in the X and Y. The coordinate of Z took the values of roughness for coordinate Z, these patches have been drawn in order to show the difference between the T-spline surface and NURBS surface. Figure (11) shows roughness drawn by MATLAB software for T-spline surface and NURBS surface.



(a) T-spline surface (bicycle seat) (b) NURBS surface (bicycle seat)

Figure (10): points that were measured for roughness and Gaussian curvature for the bicycle seat models.

Table (7): The values of roughness and Gaussian curvature for the T-spline bicycle

X	Y	Ra (μm)	Gaussian curvature
36	24	2.21	5.29462e-16
36	32	2.51	-3.66342e-16
36	40	2.11	-1.35464e-16
36	48	2.11	-7.1595e-16
36	56	2.31	-4.81901e-16
36	64	2.41	1.52729e-16
50	24	2.31	-5.7301e-15
50	32	2.12	5.0297e-17
50	40	2.61	-3.16843e-16
50	48	2.28	-1.7984e-16
50	56	2.11	1.12326e-16
50	64	2.33	-4.51023e-17
64	24	3.19	-6.02312e-15
64	32	3.22	3.10039e-16
64	40	2.94	1.13732e-15
64	48	2.64	7.75803e-16
64	56	2.81	8.0111e-16
64	64	2.53	3.11699e-16

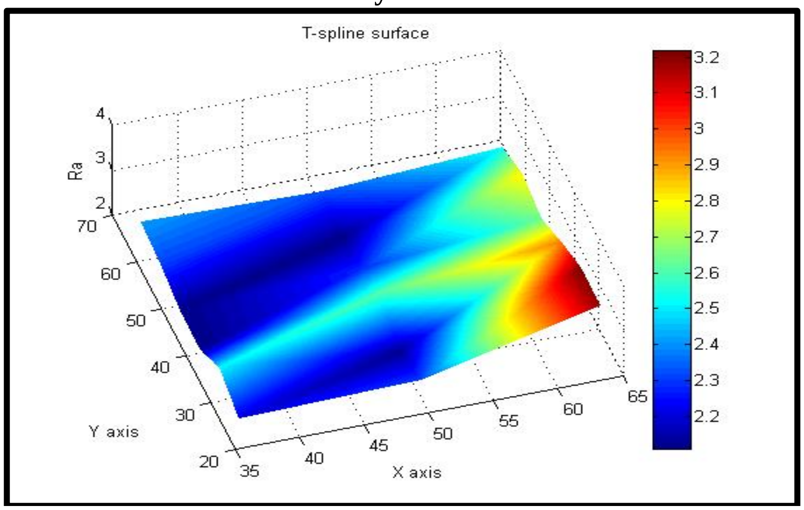
seat model.

X	Y	Ra (μm)	Gaussian curvature

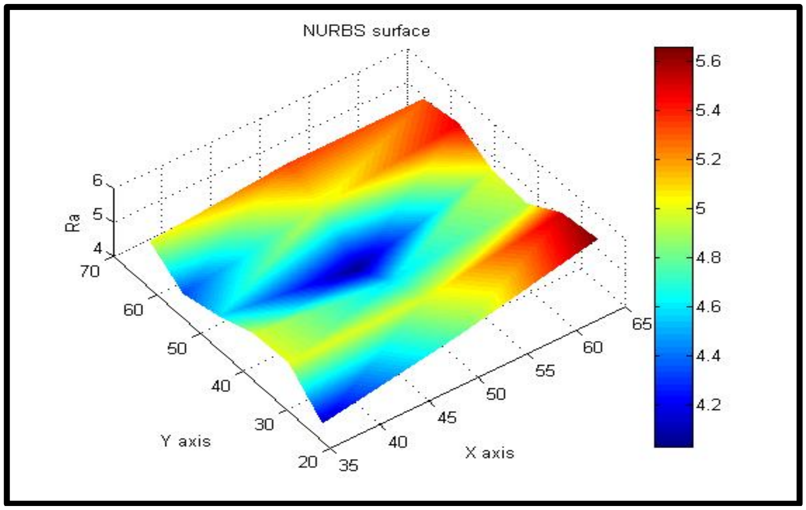
Table (8): The values of roughness and Gaussian curvature for the

36	24	4.12	0
36	32	5.00	0
36	40	4.97	0
36	48	4.58	0
36	56	4.33	0
36	64	4.99	0
50	24	4.78	0
50	32	4.98	0
50	40	4.57	0
50	48	4.03	0
50	56	4.98	0
50	64	5.34	0
64	24	5.66	0
64	32	5.54	0
64	40	4.92	0
64	48	5.01	0
64	56	5.48	0
64	64	5.31	0

NURBS bicycle seat model.



(a) T-spline surface (bicycle seat)



(b) NURBS surface (bicycle seat)

Figure (11): Roughness for T-spline surface and NURBS surface.

Results and Discussion

1. In data structure analysis, T-Splines surfaces typically have 50-70% less Geometric data structure [surfaces , 3d curve , 2d curves , vertices , edges , trims , loops , faces] than the equivalent NURBS surface, allowing for faster and more controlled direct editing and shape optimization.
2. In Gaussian Curvature Analysis, the T-Spline surface for the bicycle seat model and longitudinal section of the bottle model have positive and negative Gaussian curvature values. Positive Gaussian curvature value means the surface is bowl-like and negative Gaussian curvature value means the surface is saddle-like and the NURBS surface, Gaussian curvature is equal to zero because NURBS surfaces have a rectangular topology and a zero value means the surface is flat in at least one direction.
3. In measurement runtime for machining (roughing and finishing), the T-Spline surface for the bicycle seat model is machined in 16 minutes less than machining the NURBS surface, and the T-Spline surface for the longitudinal section of the bottle model is machined in 10 minutes less than machining the NURBS surface because of the data structure in T-Splines surface less than the NURBS surface, The time is money and time affects the production lines.
4. In measurement of roughness, the T-Spline surface for the bicycle seat model has 2.4861 (µm) average (Ra) for patches which were used to measure roughness average (Ra), and the NURBS surface has 4.9216 (µm) average (Ra) for patches which were used to measure roughness average (Ra), This means that the T-Spline surface resulting from machining is smoother than of that NURBS surface resulting from the machining.

Conclusions

1. T-spline is easy to create and modify free form and organic designs model shapes of any complexity.
2. Creates more design variations in less time and creates non-rectangular surfaces

and break free from the limitations of traditional NURBS surface modeling.

3. T-Splines surfaces typically have 50-70% less control points than the equivalent NURBS surface, allowing for faster and more controlled direct editing and shape optimization.

4. T-Spline surfaces are watertight and very easy to smooth, making them ideal for analysis and manufacturing.

5. Model a complete shape as a single fluid and continuous surface, eliminating the need to match continuity across patch boundaries.

6. T-spline surfaces operate on much lesser control points than NURBS surfaces but are having the best quality.

7. The most important conclusion is that the process for machining (roughing and finishing) for the T-Spline surface model is carried out in a shorter time than machining the NURBS surface. The time is money and time affects the production lines.

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