Methodology framework for surface shape evaluation

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Abstract— This paper treats interdisciplinary topics for alternative surface analysis and its evaluation. Analysis methodology and its results can be used in design and styling to tell us what kind of surface shapes are present. Advanced graphical algorithm tool Grasshopper® (GH) is used to build analysis procedure. Several new introduced approaches are used and briefly presented. A framework of simplified classification is also presented, where similarity with color valuation can be seen. GH's procedure builds quite complex bundle of components and connections therefore just major steps in this algorithm are explained.

Keywords— analysis, design, methodology of surface evaluation

I. Introduction

A SURFACE of designed object is the communication language that interacts with users. This framework of methodology that analyses existing products is a great tool for numerical shape evaluation. Furthermore the analysis can be used to achieve products with well styled and designed surface. The procedure and its practical use is presented in following chapters.

Different practical exams are shown in this chapter. First the fundamental surfaces are analyzed. Analysis of two real objects follows. The results and discussions related to the analysis using the developed shape evaluation procedure are included into this chapter.

II. Theoretical part

A. *Review of related works*

Shape usually starts with simple curve and furthermore with 2D drawing as described in [1] and [2]. This 2D drawing impacts 3D shape of an object. In the FIORES project [3]-[8] mayor researchers proposed several terms for styling properties and features in CAID. By means of questions and observation of communication between stylists and engineers, a list of terms that describe the styling properties was composed. These are:

- Radius/Blending
- Convex/Concave
- Tension
- Straight/Flat
- Hollow
- Lead in
- Soft/Sharp
- S-Shaped
- Crown
- Hard/Crude
- Acceleration [3]-[8]

Some of these terms for specific properties are very similar or unclear and need to be refined. Therefore we tried to simplify them into a new classification.

Interesting classification of relative distances (RD) and directional fragmentation (DF) of 2D boundary shapes was presented in [9]. Method uses property that different shapes have different combinations of RD and DF. Shape presentations of different rooms, cities and states were used in experimental part. Several other classification methods were presented in [9] but mostly for 2D shapes.

Methods for analysing aesthetic impression of curves have already been developed. Considering Harada [10] are those curves parts of logarithmic graphs. Graph curvature in dependence of path – K(s) and K-vector in logarithmic curvature histogram (LCH) were observed. Aesthetic curve was defined as a curve whose LCH is a straight line. Authors in [11] used this method to determine objects' impression. They provided CAD system which can *feel* the same impression on curved surfaces like human designers can. On the base of LCH they proposed three types of surfaces by human impression: convergent, divergent and neutral. They observe some Japanese objects and conclude that they have convergent impression and European objects divergent impression. According LCHs five general classes for aesthetic curves were proposed: minus, zero, plus, plus-minus and minus-plus [10]. Other authors in [12] have also observed and analysed spatial aesthetic curve segments. They created graphs K(s) and LCHs of those curves. Author Yoshida evaluated aesthetic curves, which can be considered as a generalization of the Clothoid, the logarithmic spiral, the circle involute, and the circle in [13].

B. *Methodology*

Methodology of surface evaluation is developed to establish the meta-language in design communication which was perceived as necessary part of styling in [3]-[8]. The first step is analysis of existing geometry and the second is synthesis of newly created geometry considering desired property.

Early stage of classification of surfaces has already been proposed in [14]. Furthermore the classification was changed to be simpler and more logical and is still under development.

Five classes are now shrunken into three properties that are characterising surfaces similar as colours in color space [15], where each colour is presented as a mix of values L*, a* and b*. Our geometrical space consist of these three axes:

- Curvature – **C**

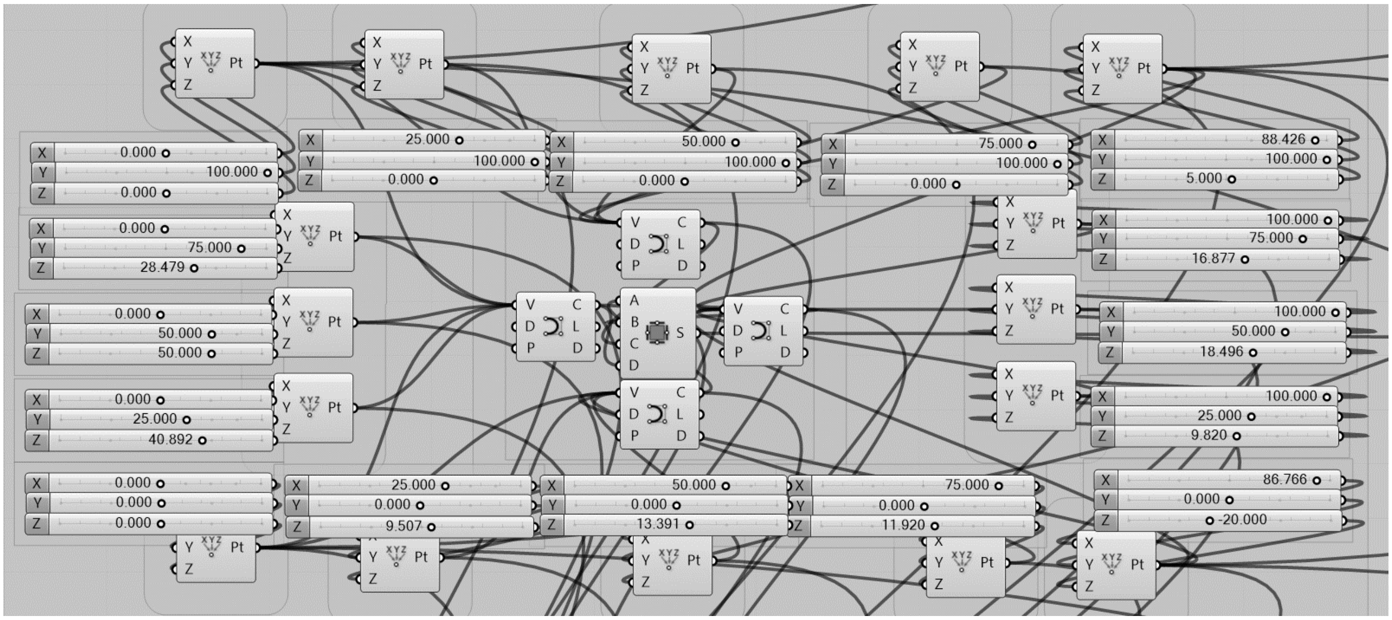


Fig. 1 Small fragment of GH canvas and nxn procedure.

- Symmetry – **S** and
- Substantialness –**B**

Therefore a surface is indicated as (C, S, B), where curvature goes from – to + sign. Zero determinates neutral curvature and means plane. Negative values mean concave surface and positive values are for convex surfaces. They are evaluated with sign and values of entities in nxn matrix. Value is calculated as arithmetic average of normalized nxn distances including preposition sign.

Symmetry takes just positive values. Zero means perfect symmetry of a surface observed over middle column of nxn matrix. Symmetry can be detected as differences between entities pairs compared over middle column. The first and last column are compared and second and the last but one. The middle one stays untouched in this case. Symmetry is calculated as arithmetical average of all entity pairs.

Substantialness is third property to indicate size or width of the surface. We have had discussions about this property name because terms are limited and it is not easy to take the proper one. Terms “solid” and “slim” were also in discussion but we take substantialness because it describes property better. It is calculated as ratio between length and width of the observed surface projected on triangular plane.

1) Grasshopper’s procedure

Grasshopper® (GH) is a graphical algorithm tightly integrated with 3D modelling tool Rhinoceros (RH). Grasshopper is an add-on and runs within the RH application. Procedures are created by dragging components onto a canvas as presented in figure 1. Outputs of these components are then connected to the inputs of subsequent components. Grasshopper is mainly used to build generative algorithms and it acts like a programming tool. Many of Grasshopper’s components create 3D geometry. Procedures may also process other types of algorithms including numeric, textual, audio-visual or haptic applications.

GH is used because of complex algorithms that can be used out of the box and can be easily connected and combined.

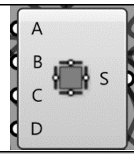
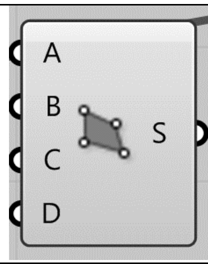
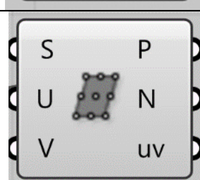
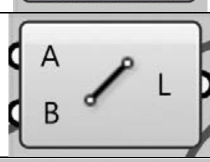
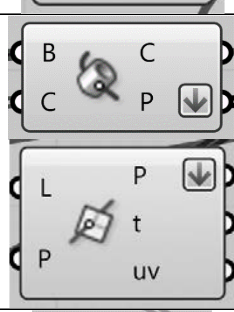
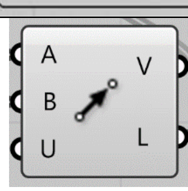
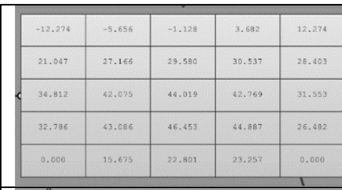
First we have to explain prefix “nxn”. Nxn comes from GH procedure where 5x5 point grid is used to define number of intersections. N has to be odd number and can be changed from 3x3 up. But to show fundamental functionality the grid 5x5 shows enough details therefore whole nxn procedure basis on 5 by 5 points.

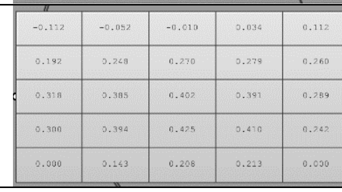
GH nxn procedure is a new approach in surface evaluation. It became quite complex bundle of components and connections. Therefore is hard to show whole procedure in one view. One fragment of GH procedure is shown in figure 1. This part defines four bounding curves which build Coons patch surface hereinafter. This “synthetic” surface is then evaluated in nxn analysis core.

Furthermore curvature graph K(s) and LCH on selected curve on surface can be calculated and presented. Practical use of those graphs is shown in experimental part hereinafter. K(s) and LCH charts are already known [10]-[13] and are here used for fair curve evaluation. Some more analyses are shown in [16]. Curvature is analyzed and shown on several practical examples.

GH nxn procedure requires input geometry as synthetic surface, mesh or imported NUBS surface. From type of input geometry depends how GH procedure starts. Analysis core stays the same. Short preview of steps for surface shape evaluation in GH nxn procedure is shown in table 1. Several logical steps are present where every following step has an input of one or more previous components. Hereinafter are shown graphical results of GH nxn procedure.

Table 1 Short preview of steps for shape evaluation in nxn procedure.

<table>
<tr><td rowspan="3">Step 1:</td><td rowspan="3">Input geometry</td><td>Synthetic surface or</td><td>
</td></tr>
<tr><td>Imported 3D mesh or</td><td></td></tr>
<tr><td>Imported NURBS surface.</td><td></td></tr>
<tr><td>Step 2:</td><td colspan="2">Triangle plane through point A, B and C.</td><td>
</td></tr>
<tr><td>Step 3:</td><td colspan="2">Projection of input surface on triangular plane.</td><td>
</td></tr>
<tr><td>Step 4:</td><td colspan="2">Offset of projection on both sides.</td><td>
</td></tr>
<tr><td>Step 5:</td><td colspan="2">5x5 points segmentation on offsets.</td><td>
</td></tr>
<tr><td>Step 6:</td><td colspan="2">Lines through segmentation points.</td><td>
</td></tr>
<tr><td>Step 7:</td><td colspan="2">Creating points on intersections of lines with input surface and lines with planar surface.</td><td>
</td></tr>
<tr><td>Step 8:</td><td colspan="2">Nxn vectors starting at intersection points on triangular plane and ending at intersection points on input surface.</td><td>
</td></tr>
<tr><td>Step 9:</td><td colspan="2">Nxn matrix of lengths and directions of nxn vectors.</td><td>

-12.274	-5.656	-1.128	3.682	12.274
21.047	27.166	29.580	30.537	28.403
34.812	42.075	44.019	42.769	31.553
32.786	43.086	46.453	44.887	26.482
0.000	15.675	22.801	23.257	0.000
</td></tr>
<tr><td>Step 10:</td><td colspan="2">Normalized lengths and directions of nxn matrix.</td><td>

-0.112	-0.052	-0.010	0.034	0.112
0.192	0.248	0.270	0.279	0.260
0.318	0.385	0.402	0.391	0.289
0.300	0.394	0.425	0.410	0.242
0.000	0.143	0.208	0.213	0.000
</td></tr>
</table>

a) Step 1

Three types of input geometries are acceptable.

First is synthetic surface, generated with part of our GH procedure. This part of procedure is shown in figure 1. Surface is defined with four bounding curves. Every curve is defined with five points. Each point has three coordinates that can be manipulated. It is important to make proper smooth surface which is not overlapped or wrinkled.

Second input is mesh that can be obtained, inter alia, with 3D scanner. The so called nxn frame has to be defined first. The nxn frame determines observation area of the mesh and has to be defined manually in this analysis.

Further steps present analysis core of GH procedure hereinafter that is same for any type of input geometry.

b) Step 2

Through points A, B and C is defined triangular plane presented in figure 2. This triangle also defines direction of the surface. Considering Podehl [5] are natural directions from bottom to top and from left to right. In this framework the direction is determined manually and should present orientation of the surface in space according products use.

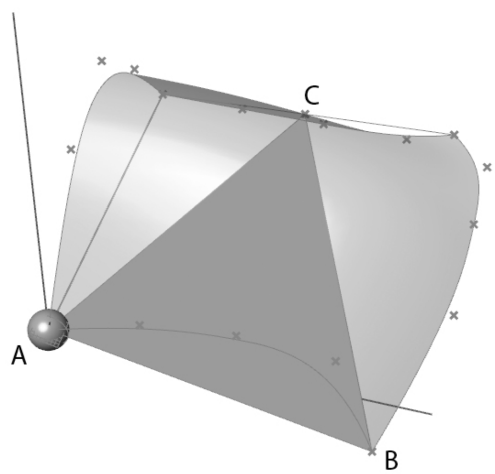


Fig 2 Triangular nxn plane defined with point A, B and C which shows natural direction of analyzed surface “UP”.

Distance from point A to point C is also defined as nxn length used for distances normalization hereinafter. Point A and B are placed at the corners of the bottom edge of the surface. Point C is in the middle of the line that connects upper

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corners of the surface as explained in figure 2.

c) Step 3

Surface is projected on the same plane as triangular nxn plane lies. The planar nxn surface projection is created as shown in figure 3 marked with darker color.

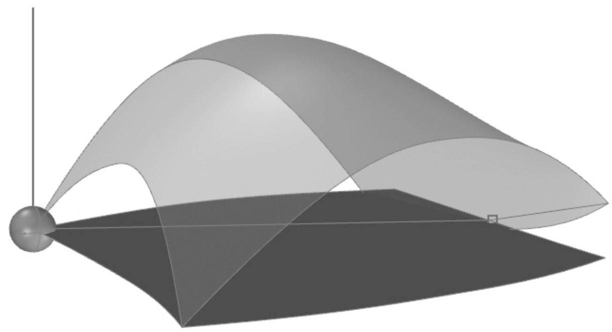

Fig 3 Surface is projected on the same infinite plane as triangular nxn plane lies.

d) Step 4

There are created two offsets on each side of the planar surface projection as figure 4 shows. Distance of both offsets can be changed and should be far enough not to intersect the analyzed surface.

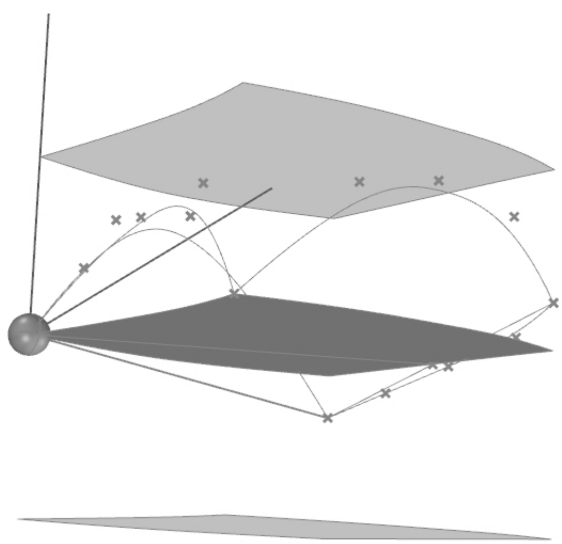

Fig 4 Two offset on each side of projected surface are created.

e) Step 5

This step provides surface segmentation with point grid 5 by 5 points on both offsets shown in figure 5.

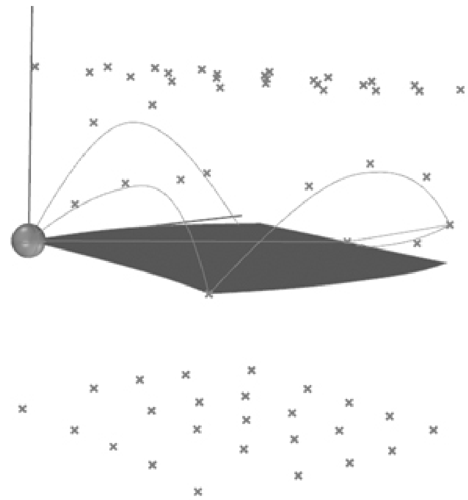

Fig 5 Both offset surfaces are segmented with 5x5 points.

f) Step 6

Point on both offsets are paired and connected with parallel lines with starting points on one offset and ending on other.

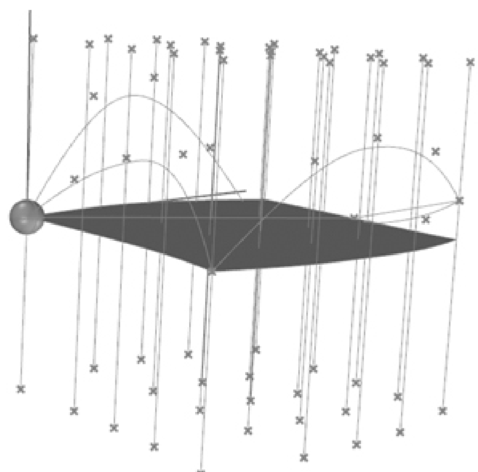

Fig 6 Segmentation points are connected with lines.

g) Step 7

Intersection points between lines and analyzed surface are marked in step 7. Similar are marked intersection points on planar projected surface.

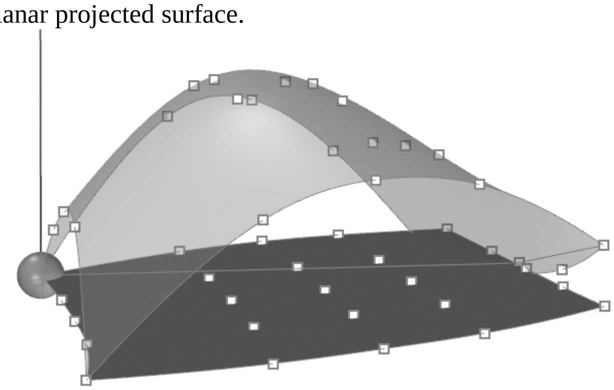

Fig 7 Intersection points between lines and analyzed surface are created and intersection points between lines and projected planar surface are created.

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h) Step 8

In step 8 a vector field is created. Vectors have starting points at projected planar surface and ending points at intersection points on analyzed surface. Vectors are used because they have direction that is important to correctly determine curvature of surface. This direction is considered furthermore as positive or negative sign of value in nxn matrix.

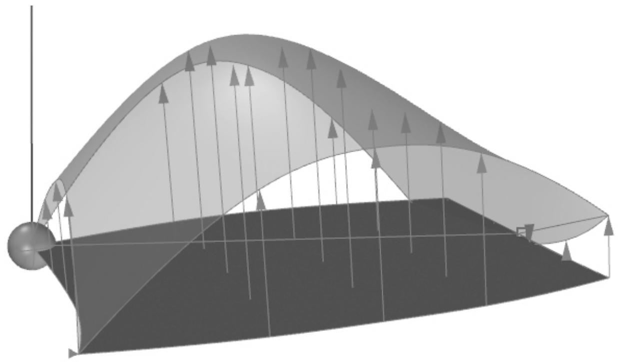

Fig 8 Vectors are connecting intersection points.

i) Step 9

The results of nxn analysis as actual distance with preposition sign are shown in table 2. Negative sign of the value means that the vector shows down. Or with other words; the surface lies under the nxn triangular plane. Table 2 presents analysis for the surface shown in figure 3, 7 and 8.

Table 2 The results of nxn analysis as actual distances with preposition sign.

-12.274	-5.656	-1.128	3.682	12.274
21.047	27.166	29.580	30.537	28.403
34.812	42.075	44.019	42.769	31.553
32.786	43.086	46.453	44.887	26.482
0.000	15.675	22.801	23.257	0.000

The nxn matrix also follows natural directions and is not the same as in mathematical writing. It has swapped rows over middle row. So the matrix starts with entry (0,0) at bottom left corner as shown in form (1).

$$\begin{bmatrix} a_{n-1,0} & \cdots & a_{n-1,n-1} \\ \vdots & . & \vdots \\ a_{0,0} & \cdots & a_{0,n-1} \end{bmatrix} \qquad \text{Form (1)}$$

Starting point marked with (0,0) is at the bottom left side on analyzed surface, same as in nxn matrix. This enables to locate position of same point in 3D space and in nxn matrix.

j) Step 10

Table 3 The results of nxn analysis as normalized distances with preposition sign.

-0.112	-0.052	-0.010	0.034	0.112
0.192	0.248	0.270	0.279	0.260
0.318	0.385	0.402	0.391	0.289
0.300	0.394	0.425	0.410	0.242
0	0.143	0.208	0.213	0

Nxn matrix collects normalized values of distances, combined with directions. Normalized means that every nxn distance is divided by value of nxn length. Nxn length is shown in figure 2 as distance A-B. With normalization the size of an object is irrelevant. Entities (0,0) and (0,4) have always value 0. All other values can be positive or negative depending of the analyzed surface.

III. Experimental Part

Different examples are shown in this chapter. First the fundamental surfaces are analyzed. This synthetic surfaces are created with procedure, shown in figure 1. At the end are two applicative cases. First is analysis of headlight of a car.

A. Fundamental surfaces

Some fundamental synthetic surfaces are shown in this chapter. Appropriate vectors were created with nxn procedure as shown in figures 11 to 14. Numerical result are shown in tables 4 to 6. Negative sign means the direction of vector downwards (-Z). Values for C,S and B numerical results are marked with bold text.

1) Plane

Analysis of not curved synthetic surface gives an nxn matrix with zeroes while there are no vectors to create. Boundary points have all Z coordinate zero. All points are equally arranged in X and Y direction in steps: 0, 25, 50, 75 and 100 units and have appropriate coordinates.

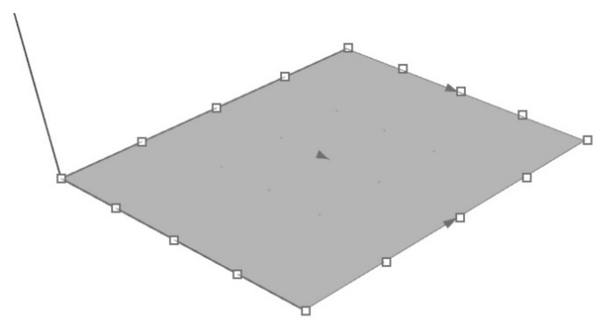

Fig 10 Synthetic plane.

Table 4 The results of nxn analysis as actual distances with preposition sign.

0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00

C= 0
S= 0
B= 100

2) Simple symmetrical convex surface

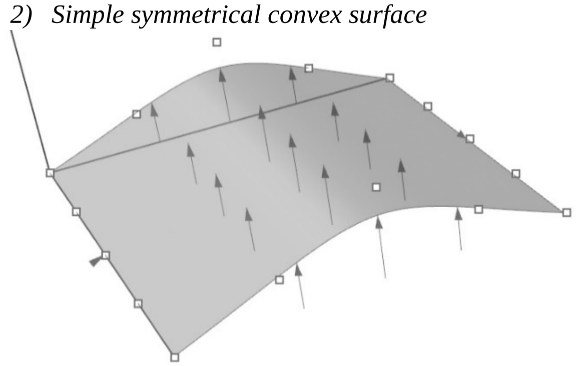

Fig 11 Simple synthetic symmetrical convex surface.

Table 5 The results of nxn analysis as actual distances with preposition sign for convex surface.

0.00	0.00	0.00	0.00	0.00
0.11	0.11	0.11	0.11	0.11
0.16	0.16	0.16	0.16	0.16
0.11	0.11	0.11	0.11	0.11
0.00	0.00	0.00	0.00	0.00

C= 7,6
S= 0
B= 100

3) Simple symmetrical concave surface

Simple symmetrical concave surface was created as shown in figure 12.

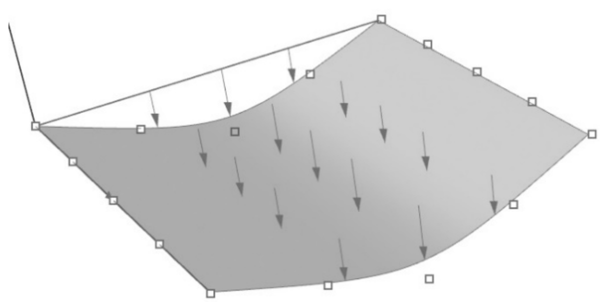

Fig 12 Simple synthetic symmetrical concave surface

Table 6 The results of nxn analysis as actual distances with preposition sign for concave surface.

0.00	0.00	0.00	0.00	0.00
-0.11	-0.11	-0.11	-0.11	-0.11
-0.16	-0.16	-0.16	-0.16	-0.16
-0.11	-0.11	-0.11	-0.11	-0.11
0.00	0.00	0.00	0.00	0.00

C= -7,6
S= 0
B= 100

4) Two directional symmetrical concave surface

Figure 13 shows concave surface bended in two directions (X and Y).

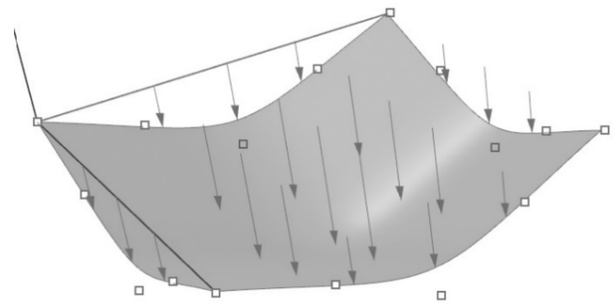

Fig 13 Synthetic two directional (X and Y) symmetrical concave surface.

Table 7 The results of nxn analysis as actual distances with preposition sign for two directional concave surface.

0.00	-0.11	-0.16	-0.11	0.00
-0.11	-0.22	-0.27	-0.22	-0.11
-0.16	-0.27	-0.31	-0.27	-0.16
-0.11	-0.22	-0.27	-0.22	-0.11
0.00	-0.11	-0.16	-0.11	0.00

C= -15,21
S= 0
B= 100

5) Inflection surface

Synthetic inflection surface has positive vectors in one direction and negative in other direction as shows figure 14.

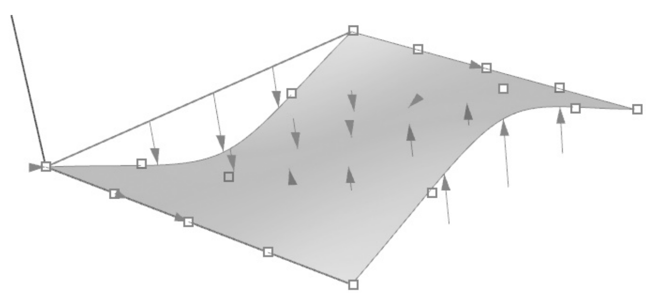

Fig 14 Synthetic inflection surface has vectors in positive and negative direction.

Table 8 The results of nxn analysis as actual distances with preposition sign for inflection surface.

0.00	0.00	0.00	0.00	0.00
-0.11	-0.06	0.00	0.06	0.11
-0.16	-0.08	0.00	0.08	0.16
-0.11	-0.06	0.00	0.06	0.11
0.00	0.00	0.00	0.00	0.00

C= 0
S= 200
B= 100

B. Real 3D scans

Two real objects were 3D scanned are analyzed with nxn procedure in this section. First is the front headlights surface and second is tail of a sports car. Nxn matrix, K(s) and LCH are shown in both cases. Sports car hood was reverse engineered with Rhinoceros add-in T-splines. This add-in

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enables A-class surfaces creation that are very important in product design to achieve good looking design.

a) Front headlights surface

Figure 15 shows scan of a real object. The classification is still under development therefore a table 9 will be explained and not token as an absolute result. The surface is more extended inwards on the right side, therefore are in the most right column negative values. The surface shows convexity in the lower middle side because there are the highest values, marked with gray in table 9.

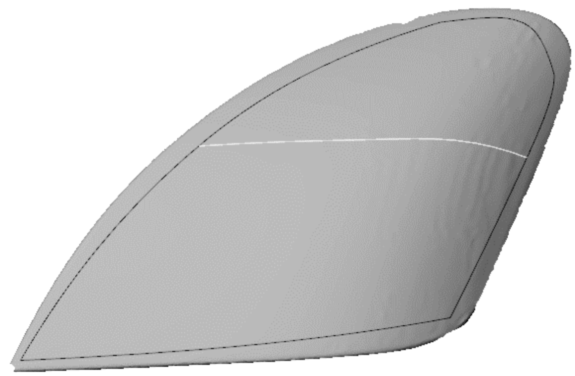

Fig 15 Front headlights surface with section curve.

Table 9 The results of nxn analysis as actual distances with preposition sign.

0,017	0,010	0,002	-0,009	-0,027
0,050	0,052	0,050	0,028	-0,030
0,070	0,081	0,085	0,058	-0,022
0,056	0,079	0,092	0,073	-0,010
0,00	0,037	0,063	0,063	0,00

C= 3,467
S= 110,2
B= 59,3

Fig 16 Graph K(s) and LCH of section curve of the headlight.

Section curve of headlight shown in figure 15 is analyzed. Figure 16 presents K(s) graph on the left side and LCH on the right side. Graph K(s) shows smooth chart except at peak. That means the section line presents smooth curve excepting this location where curvature changes drastically. LCH is unequal and does not show any specific property.

b) Sports car tail

Real sports car was scanned and reverse engineered. Good NURBS surfaces transitions were desired by a customer. Anyway existing global shape of a car must be followed. Therefore was compromised where some minimal shape changes were allowed and where not.

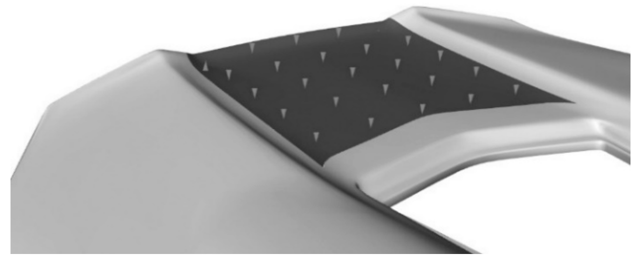

Fig 17 Darker surface of reverse engineered sports car tail was analyzed with nxn procedure.

On the tail of sports car was created transverse section curve for curvature analysis as shown in figure 18.

Table 10 The results of nxn analysis as actual distances with preposition sign.

-0.011	-0.007	0.000	-0.007	-0.011
-0.009	-0.009	-0.002	-0.009	-0.009
-0.007	-0.011	-0.004	-0.011	-0.007
-0.005	-0.012	-0.008	-0.012	-0.005
0.000	-0.012	-0.009	-0.012	0.000

C= -0,75
S= 0
B= 78

The table 10 shows the concavity of analyzed surface while most of the values are negative.

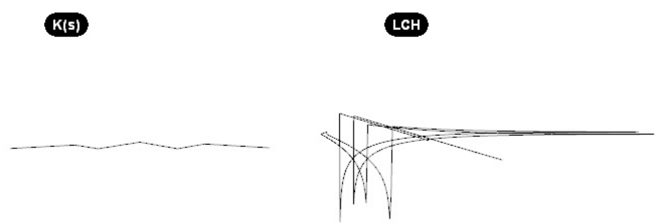

Fig 18 K(s) and LCH charts of sports car tail section.

Figure 18 shows graph K(s) on the left side where minimal symmetrical waving is detected. On this part the existing shape of a car was followed by creating this surface with T-splines.

LCH on the right side of figure 18 presents piecewise beautiful section curve while histogram has straight line curve as part of it. That proves that surfaces and consequently section curves drawn with T-splines are fair curves as shown in [10].

IV. DISCUSSION

The results of nxn procedure are presented in previous section as numerical values C, S and B. These values allow us to evaluate surfaces. On that base they will be distributed in several classes later on.

C is for curvature and is zero if the surface is flat and presents a plane. For positive values the surface is convex and for negative it is concave.

S is for symmetry. Zero symmetry means perfect symmetrical surface. All the values are processed with absolute value therefore are just positive. Greater the value more is surface asymmetric.

B is for substantialness and can be only positive. 100 means equal width and height of the surface. All other values are between 0 and 100. At 0 there is just one curve and not surface any more therefore it will not be used.

V. Conclusions and Future Work

Methodology framework for evaluation of surfaces using nxn procedure gives us reasonable results for surface evaluation on cases described in chapter III. It cannot be discussed about classification of results at this stage while it is still under development.

As additional the fairness of section curves can be evaluated as shown in case Sports car tail. Here we get thus an analytical tool for the design features checking and errors detection.

Whole nxn procedure could be implemented using any programming language like C++ or java and operated like standalone program or add-on for different programs.

This development model makes sense so it can be used for expert system support for the design of complex products, among which is certainly in the first place car design. Proposal of intelligent advisor system was presented in [17].

In order to achieve desired refinements and fine-tuning of our shape evaluation procedure and methodology for surface shape evaluation we are continuously adding a substantial number of new examples – scans of real objects from a variety of areas of product design.

References

[1] V. Cheutet, C. E. Catalano, J. P. Pernot, B. Falcidieno, F. Giannini, and J. C. Leon, "3D sketching for aesthetic design using fully free-form deformation features," *Comput. Graph.*, vol. 29, no. 6, 2005, pp. 916–930.

[2] V. Cheutet, "2D semantic sketcher for car aesthetic design," *CPI2007*, 2007.

[3] F. Giannini, M. Monti, and G. Podehl, "Aesthetic-driven tools for industrial design", Journal of Engineering Design, Vol. 17, No. 3, 2006, 193–215.

[4] F. Giannini, M. Monti, and G. Podehl, "Styling properties and features in computer aided industrial design", Computer Aided Design & Applications, Vol. 1, No. 1–4, 2004, 321–330.

[5] G. Podehl, "Terms and Measures for Styling Properties", 7th International Design Conference – Design 2002, 2002, 879–886,

[6] F. Giannini, "A Survey to Evaluate how non Designers Perceive Aesthetic Properties of Styling Features," Comput. Aided. Des. Appl., vol. 10, no. 1, 2012, pp. 129–138.

[7] F. Giannini, M. Monti, and G. Podehl, "Styling properties and features in computer aided industrial design," *Comput. Aided. Des. Appl.*, vol. 1, no. 1–4, 2004, pp. 321–330.

[8] F. Giannini, E. Montani, M. Monti, and J.-P. Pernot, "Semantic evaluation and deformation of curves based on aesthetic criteria," *Comput. Des. Appl. Comput. Des. Appl.*, vol. 8, no. 3, 2011,pp. 449–464.

[9] E. Shpuza, "A Coupled Configurational Description of Boundary Shape Based on Distance and Directionality," Artif. Intell. Eng. Des. Anal. Manuf., vol. 25, no. 4, 2011, pp. 357–374.

[10] Harada, T., Yoshimoto, F., & Moriyama, M. "*An Aesthetic Curve in the Field of Industrial Design*". In Proceedings of the IEEE Symposium on Visual Languages. Washington, DC, USA: IEEE Computer Society. 1999

[11] Kanaya, I., Nakano, Y., & Sato, K. *Simulated Designer's Eyes — Classification of Aesthetic Surfaces*. Design Discourse, Vo.l II(No. 4) 2007

[12] N. Yoshida and T. Saito, "Compound-Rhythm Log-Aesthetic Curves," vol. 6, no. 1, 2009, pp. 1–10.

[13] N. Yoshida and T. Saito, "Interactive aesthetic curve segments," *Vis. Comput.*, vol. 22, no. 9–11, 2006, pp. 896–905.

[14] Cupar, A, Pogacar, V, Stjepanovic, Z. "Methodology for Analysing Digitised Geometry", Chapter 56 in DAAAM International Scientific Book 2013, 2013,pp. 903-920, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-901509-94-0, ISSN 1726-9687, Vienna, Austria

[15] Available from: http://dba.med.sc.edu/price/irf/Adobe_tg/models/cielab.html

[16] A. Cupar, V. Pogacar, and Z. Stjepanovic, "Methodology for Surfaces Analysis and Classification," *Univers. J. Mech. Eng.*, vol. 2, 2014, pp. 64–70.

[17] J. Kaljun, U. Sancin, G. Harih, and B. Dolšak, "Aesthetics as parameter of intelligent design support," 2012, pp. 1293–1300.