Genetic Algorithm for Correcting Fine Structure of Surfaces by Highlight-lines

György Gyurecz[1] , Dr. Gábor Renner[2]

[1] Institute of Machine Design and Safety Engineering, Óbuda University
[2] Computer and Automation Research Institute, Hungarian Academy of Sciences

***Abstract**: Highligh lines is a powerful method for quality evaluation and fine error disclosement of class A surfaces. We propose a tool that enables the designer to correct fine surface errors and improve the quality of class A surfaces, by adjusting its highlight lines. The adjustment is carried out by replacing the defective parts with highlight line curves of designer's intent. The parameters of the corrected surface, corresponding to the highlight line adjustment is determined by a genetic algorithm (GA). The paper discusses genetic representation and fitness function developed for the specific problem and gives an usability analysis of the method. The advantage of the method is its robustness and applicability to surfaces of any shapes, and any kinds of CAD representations.*

***Keywords**: surface errors; highlight lines; genetic algorithm*

1 Introduction

Class A surfaces are those outer parts of industrial objects which attribute to their aesthetic appeal. The most important class A surfaces are those representing car, airplane and ship hulls, household appliances, etc. The design of class A surfaces thus involves not only functional criteria but also subjective ones related to style and appearance. Creating tools which support the work of a stylist is a challenging task in the areas of CAD and CAGD. Design criteria and tools include highlight line based evaluation and modeling.

The development of highlight line display method is attributed to Klaus-Peter Beier and Yifan Chen [1]. Methods for designing surfaces by the adjustment of highlight lines were introduced by Klass [8] and later Kaufmann and Klass [9]. Correlation between highlight lines and the defining parameters of the surfaces i.e. control points (CP) is established by a non-linear equation system, which is too time consuming to solve, and the results are not always good enough. The method developed by Zhang and Cheng [10] introduces a great number of simplifications to obtain a linear system of equation to modify control points through highlight lines. However, the highlight line cannot accurately follow the points specified by the designer and the method yields adequate results only in a small range of the errors.

The above methods try to handle the complex mathematic relation between the adjusted highlight line and the defining parameters of the corresponding surface. We propose a method that solves this problem by genetic algorithms (GA), which can find modified control points even in the absence of direct mathematical relations.

The proposed method of surface correction starts with the computation of highlight lines (Figure 1). Inspection of the surface quality is carried out by several light-source settings and surface orientations. Then the designer selects and corrects the defective highlight lines using facilities of a CAD system. This is followed by the automatic determination of the affected surface region and corresponding control points. Adjustment of the control points is carried out by a genetic algorithm.

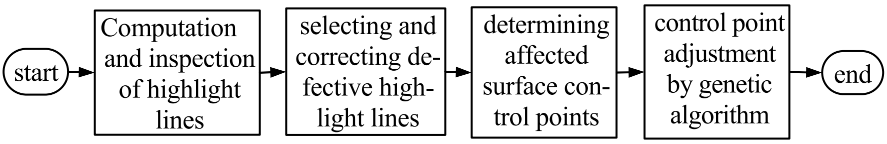

Figure 1

Block diagram of the surface correction method

2 Representation of Surfaces and Highlight Line Computation

Parametric representation of the free form surfaces in Bézier, B-spline or NURBS form, are widely used in CAD applications. These kind of representations define the shape of the surface $\mathbf{S}(u,v)$ by an array of control points $\mathbf{P}_{i,j}$ and the Bézier, B-spline or NURBS basis functions [7]. A highlight line is created on the surface by the reflection of a linear light-source of infinite length. The highlight line consists of a set of highlight points. They are points on the surface where the corresponding surface normal and the light-source intersect each other that is the perpendicular distance between them is zero. The line of the light source can be described as $\mathbf{L}(\lambda) = \mathbf{A}+\mathbf{B}\lambda$ where $\mathbf{A}$ is a point on $\mathbf{L}(\lambda)$, and $\mathbf{B}$ is a vector defining the direction of the line. The signed perpendicular distance $\mathrm{d}(u,v)$ between the normal $\mathbf{N}(u,v)$ at a surface point $\mathbf{S}(u,v)$ and the linear light source is:

$$\mathrm{d}(u,v) = \frac{\left[\mathbf{B}\times\mathbf{N}(u,v)\right]\cdot\left[\mathbf{A}-\mathbf{S}(u,v)\right]}{\left\|\mathbf{B}\times\mathbf{N}(u,v)\right\|} \tag{1}$$

For a point on the highlight line $d(u,v)=0$ holds, which must be solved for the control points of $\mathbf{S}(u,v)$. To design high quality surfaces, this relation has to be computed with high accuracy. We developed a robust method for computing points on highlight lines, which is described in detail in [3].

3 Concept of Genetic Algorithm

Genetic algorithms were introduced by J. H. Holland [6]. The basic idea is to apply the Darwinian mechanism of evolution in finding optimal solution to complex or non-linear problems. Solutions are represented by chromosomes, composed of genes that contain variable parameters of the solution. The chromosomes form a population and they are evaluated according to predefined criteria called fitness, which quantifies the optimality of the solution they represent. Chromosomes of next generations are created by genetic operators. The basic operators include selection, crossover and mutation. The algorithm runs until an acceptable solution is found. The parameters of effective GA including the applied operator types depend on the particular problem. Their selection and adjustment has to be analysed and tested carefully. A special attention must be made to the fitness function. It should be composed of terms closely related with the objective of the search.

4 Genetic Algorithm in Surface Correction

Our goal is to correct the shape of surfaces by means of their reflection characteristics through the shape and distribution of their highlight lines. The objective of GA is to adjust the parameters of surfaces resulting in a new surface shape that produces the desired highlight lines. In this paper we give details of genetic representation and fitness function. More detailed description of the GA can be found in [4].

4.1 Structure of Genes and Chromosomes

Free form surfaces are determined by a number of parameters. However, the most effective parameter for surface modification is the control point $\mathbf{P}_{i,j}$. In genetic representation those control points are included that have influence on the surface region that designer wants to optimise. They can be computed from the basis functions corresponding to particular control points. Their strength of influence is represented by the constant $b_{i,j}$ that is calculated by integrating the basis functions over the region of interest. A gene g_γ consist of control point modification $\Delta\mathbf{P}_{i,j}$ and constant $b_{i,j}$ applied to corresponding $\mathbf{P}_{i,j}$:

$$g_\gamma = \Delta\mathbf{P}_{i,j}(x, y, z,), b_{i,j}. \tag{2}$$

where x, y and z are Cartesian co-ordinates of $\Delta\mathbf{P}_{i,j}$, while γ is the identifier of genes within a chromosome. The chromosome of a surface has the following structure: $c_\beta = (g_1 \ldots g_\gamma \ldots g_J)$ where β identifies the chromosome in the population and J is the number of genes in the chromosomes.

4.2 Fitness Function

Fitness function contains geometric deviation between actual and desired highlight lines. It consists of two components: accuracy and shape similarity. Accuracy is based on the distance, while shape similarity on angle difference of tangent vectors between corresponding highlight points. Denote h_i^{des} the desired, and $\mathrm{h}_\mathrm{i}^{cur}$ the highlight line, created during the genetic search and $\mathrm{d}_i(t_k)$ the deviation between corresponding highlight points at different t parameters of highlight lines. Then, the distance error component of the fitness function is

$$\mathrm{f}_\mathrm{dist} = \sum_{i=1}^{l}\left(\sum_{k=1}^{n_i}\left(\mathrm{d}_\mathrm{i}(t_k) - \frac{1}{n_i}\cdot\sum_{k=1}^{n_i}\mathrm{d}_\mathrm{i}(t_k)\right)^2 \cdot \frac{1}{n_i}\right), \tag{3}$$

where $\mathrm{d}_\mathrm{i}(t_k) = \left|\mathrm{h}_i^{cur}(t_k) - \mathrm{h}_i^{des}(t_k)\right|$ while n_i denotes the number of examined highlight points. Variable l indicates the number of highlight lines. Angle difference of the error component f_ang is calculated in same manner, except the deviation is composed as follows:

$$\mathrm{d}_\mathrm{i}(t_k) = \arccos\left(\frac{\mathrm{h}_i^{des}(t_k)\cdot\mathrm{h}_\mathrm{i}^{cur}(t_k)}{\left|\mathrm{h}_i^{des}(t_k)\right|\left|\mathrm{h}_\mathrm{i}^{cur}(t_k)\right|}\right) \tag{4}$$

We analysed the fitness components regarding their efficiency of correcting highlight lines. We found, that distance error component promotes the creation of accurate highlight lines, but their shape similarity is often poor. Tangency error component behaves in opposite way: it promotes producing highlight lines with good shape similarity, but on the expenses of their accuracy. We eliminated the disadvantages of fitness components by letting the distance dominate in the beginning of the search and make the tangency dominate at the end. This is realized with the following fitness function:

$$\mathrm{f} \;= \mathrm{f}_\mathrm{dist}\left(w_{dist}^0 \mp \Delta w\right) + \mathrm{f}_\mathrm{ang}\left(1 - w_{dist}^0 \pm \Delta w\right) \tag{5}$$

where w_{dist}^0 is the weight of distance error component of the initial population. Expression $\Delta w = \left(2w_{dist}^0 - 1\right)\cdot\left(1 - \left(c_{var}^0 - c_{var}^{\tau-1}\right)\right)$ denotes the change in the ratio. It is driven by the change in the chromosome variability. Variables c_{var}^{0} and $c_{var}^{\tau-1}$ denote chromosome variability of the initial, and the previous generation (τ denotes the index of the current generation). The best results were achieved by using $w_{dist}^{0} = 0.75$.

4 Genetic Algorithm in Surface Correction

The efficiency of the proposed method was tested on several industrial surfaces that greatly differ from each other in size, shape and the degree of necessary improvement. Special attention was paid to tune the genetic process, in order to arrive at a fast and stable process, which at the same time reveals the desirable technical solution. The influence of different initial design conditions and that of different genetic operators and parameters on the quality and preciseness of the resulting surface were investigated. In this paper we give details of one investigation: we prove that the same final surface is achieved regardless the extent of the necessary corrections.

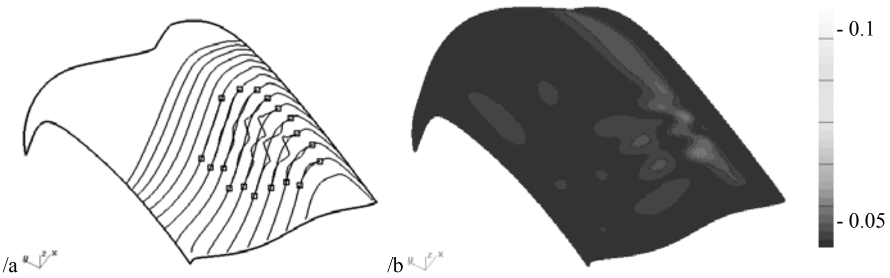

Figure 3
/a Correction of highlight lines /b Distance map between resulting surfaces

The application of the method starts with the evaluation of the reflection status of the surface. Figure 4/b displays the defective highlight lines of a car body part. Irregularities occur in the indicated region. The domain of highlight lines to be redesigned is marked by the designer (parts between bullets in Figure 3/a). The affected control points are selected automatically. Genetic search is performed with the above genetic operators and fitness function. GA runs until the user defined stop criterion is fulfilled. We defined it as 95% improvement in fitness value. Same surfaces with different quality, i.e. different error sizes in the highlight lines were taken into consideration. The results of the analysis are presented in Table 1.

The initial error defined as average distance between the desired and the defective highlight lines are highly different (more than 150%). The average distance between desired and the corrected highlight lines shows how the initial error was eliminated by an improvement of 97% and 99 % respectively. The small difference between the average distance of corrected highlight lines indicates that the algorithm converged to the same resulting surface. This can also be tackled in the distance map between resulting surfaces seen in Figure 3/b (scale is in millimetres).

Table 1

Data to measure the efficiency and robustness of the algorithm

	size_1	size_2
average distance between desired and the defective highlight lines [mm]	0.70	1.97
average distance between desired and the corrected highlight lines [mm]	0.022	0.034
improvement [%]	96.80	99.98
average distance between highlight lines of corrected surfaces [mm]	0.014	
iterations (number of generations past)	62	73

To measure the computational costs of solving the problem, we used the required number of generations. In the case of bigger error it took 73, while in case of smaller error 62 generation to reach the stop criteria. This means that the algorithm needed only 17% more computation for a surface error that caused 180% growth in the error of highlight lines.

In Figures 4 and 5 we give visual verification of results. In rendered pictures of surfaces (/a in figures) the surface seems to be free of errors. The fine structure of the surface is disclosed by highlight lines. Defective highlight lines are indicated by circles (/b in figures). The highlight lines of the corrected surfaces are shown on /c figures. Their shape, smoothness, coherence and distribution show that the surfaces are smooth and free of errors.

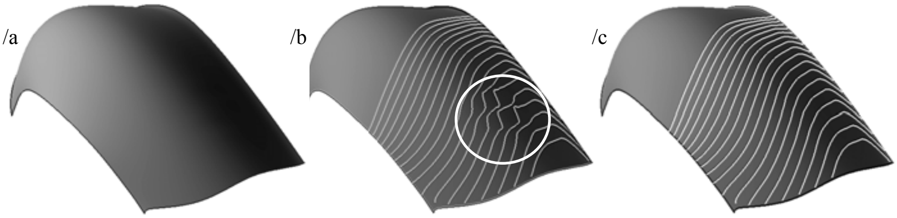

Figure 4

Surface of a chassis part before (/a, /b) and after correction (/c)

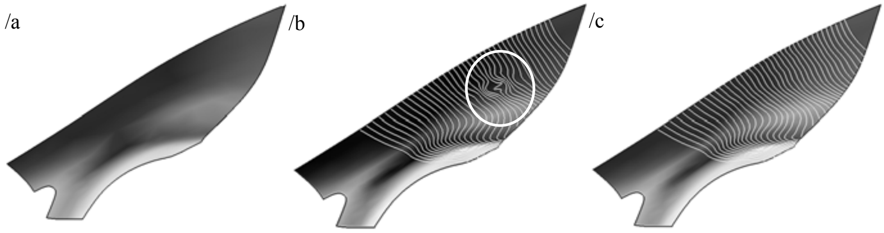

Figure 5

Surface of a car fender before (/a, /b) and after correction (/c)

Conclusion

We presented a robust and intuitive method for correcting fine surface errors by Highlight-lines. Control point modification is achieved through genetic algorithm, bypassing time consuming computing highly non-linear correlations between control points and highlight lines. Our method is applicable to surfaces of any shapes and any kinds of CAD representations, for a wide rage of highlight line and surface errors. Proportionally, the increase of computational cost is much smaller than the corresponding error size growth. Consequently, the algorithm can be more efficient when larger corrections are needed.

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