Computer-Aided Design 55 (2014) 1–12

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Surface design based on direct curvature editing[☆]

Yuki Kineri [a], Shuhei Endo [b], Takashi Maekawa [b,*]

[a] *Ricoh Co., Ltd, Japan*

[b] *Department of Mechanical Engineering, Yokohama National University, Japan*

HIGHLIGHTS

- Surface design based on direct curvature editing is introduced.
- A point-based curvature control is extended to a curve-based control.
- A log-aesthetic curve is embedded into existing design surfaces.

ARTICLE INFO

Article history:
Received 9 September 2013
Accepted 3 May 2014

Keywords:
Curvature control
B-spline curve and surfaces
Log-aesthetic curves
Cross curvature

ABSTRACT

This paper presents a novel method for modifying the shapes of existing uniform bi-cubic B-spline surfaces by interactively editing the curvatures along isoparametric curves. The method allows us to edit the curvatures of the two intersecting isoparametric curves at each knot with specified positions, unit tangents, and unit normals. The user adjusts the radii of circles, representing the radii of curvature in the u and v isoparametric directions directly via a GUI without having to work with control points and knots. Such shape specifications are converted into iterative repositionings of the control points on the basis of geometrical rules. Using these point-based curvature-editing techniques, we successfully embedded log-aesthetic curves into existing surfaces along their isoparametric curves. Moreover, we were able to distribute the cross curvature with log-aesthetic variation along the isoparametric curves. We applied our technique to the design of automobile hood surfaces to demonstrate the effectiveness of our algorithms.

1. Introduction

In the field of structural mechanics, it is well known that a higher stress concentration occurs in regions with a smaller radius of curvature [1]. The presence of such regions causes an object to experience a considerable increase in maximum stress. Therefore, engineers must design the geometry to minimize stress concentration by avoiding high curvatures. Curvature control also plays important roles in fluid dynamics. The surface curvature distribution of airfoils and blades near the leading edge is essential for optimum aerodynamic, thermoeconomic, and overall performance of turbomachinery-based power plants [2].

In aesthetic surface design, a new design can be accelerated by the reuse of existing designs if the B-spline forms are available from previous designs, in whole or part [3]. The designer can interactively make local modifications to the existing B-spline surfaces defined by knots and control points. However, modifying the surfaces to a desired shape via direct manipulation of knots and control points is difficult. Accordingly, researchers have developed tools that allow the user to change shapes of surfaces in an intuitive way and convert them into modifications in control points locations and knot vectors [4]. Séquin [5] envisioned a CAD system, in which a designer specifies boundary conditions and constraints for a car hood surface panel, and then picks a suitable cost functional, from which the system generates a desired surface via optimization.

In this paper, we introduce a novel method for modifying the shape of existing uniform bi-cubic B-spline surfaces by interactively editing the curvatures or fitting to prescribed curvature values along isoparametric curves. The *point-based* curvature control method allows us to edit the curvatures of two isoparametric curves at each knot with specified positions, unit tangents, and unit normals. Users adjust the radii of circles representing the radii of curvature of the u and v isoparametric curves via a graphical user interface (GUI), without having to work with control points and knots. Such shape specifications are converted into iterative repositionings of the control points on the basis of geometrical rules. We further extend this point-based curvature control technique to *curve-based* curvature control, where we successfully embedded log-aesthetic curves [6,7] into existing surfaces.

[☆] This paper has been recommended for acceptance by Gershon Elber.

[*] Corresponding author. Tel.: +81 45 339 3930.
E-mail address: maekawa@ynu.ac.jp (T. Maekawa).

http://dx.doi.org/10.1016/j.cad.2014.05.001
0010-4485/

The contributions of this paper can be summarized as follows:

- we introduce a novel method for editing curvatures of two isoparametric curves at the knots of uniform bi-cubic B-spline surfaces;
- we prove that changing the curvature of one isoparametric curve at a knot does not affect the curvature of the other intersecting isoparametric curve at the same knot as long as the position at the knot does not change;
- we extend point-based curvature control to curve-based control, which allows us to embed a log-aesthetic curve into the surface together with cross curvature (see Section 4.2 for definition) control.

The rest of the paper is organized as follows. In Section 2, we review the literature on direct surface curvature editing, log-aesthetic curves, and iterative geometric interpolation algorithms. In Sections 3 and 4, we examine point-based and curved-based curvature control, respectively. In Section 5, we apply our technique to the design of automobile hood surfaces to demonstrate the effectiveness of our algorithms. In Section 6, we conclude the paper.

2. Related work

In this section we review the literature on direct surface curvature editing, log-aesthetic curves, and iterative geometric interpolation algorithms.

2.1. Direct surface curvature editing

Andersson [8] developed a tool for directly modifying the curvatures of surfaces by solving non-linear partial differential equations. However, his discussions were confined to surfaces expressed as graphs of real-valued functions over the plane. Furthermore, no practical examples are given in his paper, except for a sketch of procedures.

Du and Qin [9] introduced an integrated approach that combines the partial differential equation (PDE) surfaces, and physics-based modeling techniques to allow users to interactively modify a point, normal, and curvature. The formulation results in non-linear equations, so they did not solve them precisely, but instead approximated the curvature by adjusting the distances between two neighboring points.

Eigensatz and Pauly [10] formulated an optimization framework that allows the user to directly manipulate or preserve positional, metric, and curvature constraints anywhere on the surface of a triangular mesh model.

Nasri et al. [11] presented an algorithm for interpolating curves with prescribed cross curvature on Catmull–Clark subdivision surfaces using *polygonal complexes*. However, curvature control of the feature curve was not conducted.

2.2. Log-aesthetic curves

In his review paper of CAD tools for aesthetic engineering, Séquin [5] stated that one of the key CAD problems is the embedding of beautiful or fair curves on an optimized surface and described that the most direct connection for drawing a fair curve between two points on a smooth surface is a geodesic curve [12,13]. However, sometimes the geodesic curve may be too restrictive for design purposes, as it is necessary to solve a two-point boundary value problem to connect two points. Accordingly, a designer cannot control the curve, since it is an intrinsic curve on the freeform surface. As an alternative, he suggested a curve on a surface, whose geodesic curvature is either constant or linearly varying as a function of arc-length.

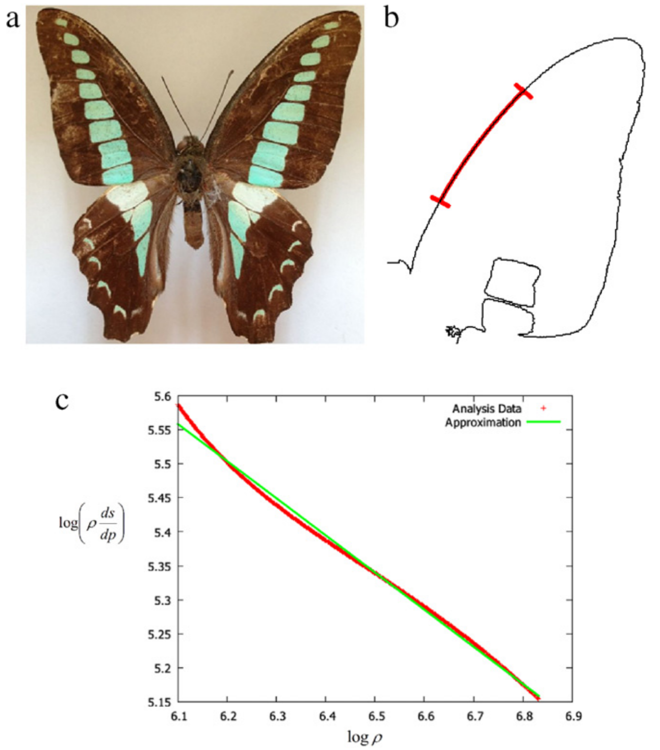

Fig. 1. (a) Blue triangle butterfly. (b) Wing boundary curves extracted by computer vision techniques. (c) Logarithmic curvature graph of (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Harada et al. [14] showed that many aesthetic curves in nature and in artificial objects exhibit monotonically varying curvature, and hence their logarithmic curvature histograms (LCH) can be approximated by straight lines. The shapes of these curves depend on the slope of LCH α, so they are called *log-aesthetic curves* [6]. We examined the shape of a butterfly wing, and a Japanese sword blade. Fig. 1(a) depicts the common bluebottle swallowtail or blue triangle butterfly whose scientific name is Graphium sarpedon, while Fig. 1(c) shows its logarithmic curvature graph, which is defined in (32) corresponding to the red curve indicated in (b). The straight line in (c) is a least squares fit having a slope of $\alpha = -0.44$. Fig. 2(a)–(c) illustrates the Japanese sword blade, its boundary curves extracted by the computer vision techniques, and the logarithmic curvature graph corresponding to the red portion in (b), respectively. It is clear from Fig. 2(c) that the logarithmic curvature graph is almost a straight line having a slope of $\alpha = -0.99$. Mathematical details of the logarithmic curvature graph are discussed in Section 4.3.

Furthermore, LCH of a clothoid curve (also called an Euler spiral or the spiral of Cornu) and the logarithmic spiral are straight lines with slopes of 1 and −1, respectively. The general formula for a log-aesthetic curve as a function of arc-length was derived by Miura [16]. Recently, Ziatdinov et al. [17] introduced analytic parametric equations for log-aesthetic curves consisting of trigonometric and incomplete gamma functions. Yoshida et al. [7] extended log-aesthetic planar curves to log-aesthetic space curves.

2.3. Iterative geometric interpolation algorithm

Recently, in contrast to the standard surface fitting methods, iterative geometric fitting methods that do not require the solution of a linear system have received attention [18–23]. These methods employ a surprisingly simple geometric-based algorithm which iteratively updates the control points in a global manner based