Friedrich Schiller University Jena
Faculty of Mathematics and Computer Science

Design and Implementation of High-Performance, Adaptive, and Robust Curve Smoothing on Surface Meshes and its Application to Medical Visualization

MASTER'S THESIS

for obtaining the academic degree

Master of Science (M.Sc.) in Mathematics

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Abstract

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Zusammenfassung

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List of Abbreviations and Acronyms

Abbreviation	Definition
iid	Independently and Identically Distributed
CDF	Cumulative Distribution Function
SLLN	Strong Law of Large Numbers
LTE	Light Transport Equation
API	Application Programming Interface
RAII	Resource Acquisition is Initialization
SFINAE	Specialization Failure is not an Error
STL	Standard Template Library

Symbol Table

Symbol	Definition
Logic	
$\exists \ldots : \ldots$	There exists ..., such that ...
$a := b$	a is defined by b.
Set Theory	
$\{\ldots\}$	Set Definition
$\{\ldots \mid \ldots\}$	Set Definition with Condition
$x \in A$	x is an element of the set A.
$A \subset B$	The set A is a subset of the set B.
$A \cap B$	Intersection — $\{x \mid x \in A \text{ and } x \in B\}$ for sets A, B
$A \cup B$	Union — $\{x \mid x \in A \text{ or } x \in B\}$ for sets A, B
$A \setminus B$	Relative Complement — $\{x \in A \mid x \notin B\}$ for sets A, B
$A \times B$	Cartesian Product — $\{(x, y) \mid x \in A, y \in B\}$ for sets A and B
A^n	n-fold Cartesian Product of Set A
$\emptyset$	Empty set — $\{\}$.
$\#A$	Number of Elements in the Set A
$\mathcal{P}(A)$	Power Set of Set A
Special Sets	
$\mathbb{N}$	Set of Natural Numbers
$\mathbb{N}_0$	$\mathbb{N} \cup \{0\}$
$\mathbb{P}$	Set of Prime Numbers
$\mathbb{Z}$	Set of Integers
$\mathbb{Z}_n$	Set of Integers Modulo n
$\mathbb{F}_m$	Finite Field with $m \in \mathbb{P}$ Elements
$\mathbb{F}_m^{p \times q}$	Set of $p \times q$-Matrices over Finite Field $\mathbb{F}_m$
$\mathbb{F}_2$	Finite Field of Bits
$\mathbb{F}_2^n$	Set of n-bit Words
$\mathbb{R}$	Set of Real Numbers
$\mathbb{R}^n$	Set of n-dimensional Real Vectors
$\mathbb{S}^2$	Set of Directions — $\left\{x \in \mathbb{R}^3 \mid \|x\| = 1\right\}$
Functions	
$f \colon X \to Y$	f is a function with domain X and range Y.
id_X	Identity Function over the Set X
$f \circ g$	Composition of Functions f and g
f^{-1}	Inverse Image of Function f
f^n	n-fold Composition of Function f
Bit Arithmetic	
$x_{n-1} \ldots x_1 x_0$	n-bit Word x of Set $\mathbb{F}_2^n$
$x \leftarrow a$	Left Shift of all Bits in x by a
$x \rightarrow a$	Right Shift of all Bits in x by a
$x \circlearrowleft a$	Circular Left Shift of all Bits in x by a
$x \oplus y$	Bit-Wise Addition of x and y
$x \odot y$	Bit-Wise Multiplication of x and y
$x \mid y$	Bit-Wise Or of x and y

Symbol	Definition
Probability Theory	
$\mathcal{B}(\mathbb{R})$	Borel σ-Algebra over $\mathbb{R}$
$(\Sigma, \mathcal{A})$	Measurable Space over Σ with σ-Algebra $\mathcal{A}$
λ	Lebesgue Measure
$\int_U f \,\mathrm{d}\lambda$	Lebesgue Integral of f over U
$\mathrm{L}^2(U, \lambda)$	Set of Square-Integrable Functions over the Set U with Respect to the Lebesgue Measure λ
$(\Omega, \mathcal{F}, P)$	Probability Space over Ω with σ-Algebra $\mathcal{A}$ and Probability Measure P
$\int_\Omega X \,\mathrm{d}P$	Integral of Random Variable X with respect to Probability Space $(\Omega, \mathcal{A}, P)$
$\int_\Omega X(\omega) \,\mathrm{d}P(\omega)$	$\int_\Omega X \,\mathrm{d}P$
P_X	Distribution of Random Variable X
$\mathbb{E}\, X$	Expectation Value of Random Variable X
$\operatorname{var} X$	Variance of Random Variable X
$\sigma(X)$	Standard Deviation of Random Variable X
$\mathbb{1}_A$	Characteristic Function of Set A
δ_ω	Dirac Delta Distribution over $\mathcal{S}^2$ with respect to $\omega \in \mathcal{S}^2$
$\bigotimes_{n \in I} P_n$	Product Measure of Measures P_n Indexed by the Set I
Miscellaneous	
$(x_n)_{n \in I}$	Sequence of Values x_n with Index Set I
$\lvert x \rvert$	Absolute Value of x
$\lVert x \rVert$	Norm of Vector x
$x \mod y$	x Modulo y
$\gcd(\rho, k)$	Greatest Common Divisor of ρ and k
$\max(x, y)$	Maximum of x and y
$\lim_{n \to \infty} x_n$	Limit of Sequence $(x_n)_{n \in \mathbb{N}}$
$\sum_{k=1}^n x_k$	Sum over Values x_k for $k \in \mathbb{N}$ with $k \leq n$
$\dim X$	Dimension of X
$\lceil x \rceil$	Ceiling Function
$\langle x \mid y \rangle$	Scalar Product
$[a, b]$	$\{x \in \mathbb{R} \mid a \leq x \leq b\}$
(a, b)	$\{x \in \mathbb{R} \mid a < x < b\}$
$[a, b)$	$\{x \in \mathbb{R} \mid a \leq x < b\}$
Constants	
∞	Infinity
π	$3.1415926535\ldots$ — Pi
Units	
$1\,\mathrm{B}$	$1\,\mathrm{Byte} = 8\,\mathrm{bit}$
$1\,\mathrm{GiB}$	$2^{30}\,\mathrm{B}$
$1\,\mathrm{s}$	$1\,\mathrm{Seconds}$
$1\,\mathrm{min}$	$1\,\mathrm{Minutes} = 60\,\mathrm{s}$
$1\,\mathrm{GHz}$	$1\,\mathrm{Gigahertz} = 10^9\,\mathrm{Hertz}$

1 Introduction

Nowadays, the majority of application domains vital to the life of humanity is supported by computer-aided systems. These are typically programs that provide a set of tools to facilitate the automatic generation, transfer, manipulation, and visualization of domain-specific data by keeping user interaction at a required minimum. Computer systems have enabled humanity to streamline processes and to abstract and encapsulate low-level tasks. As a consequence, this resulted in the ability to solve harder problems even more efficiently.

Especially in the area of medicine, examples such as the resection of liver tumors for long-term survival (Alirr and Abd. Rahni 2019) and osteotomy planning (Zachow et al. 2003), that involves reshaping and realigning bones to repair or fix bone-specific issues, show that the use of computer-aided systems for surgery planning reduces the duration of treatment and heavily increases the chance of long-term survival. Both of the named medical applications use curves on the two-dimensional reconstructed surface of scanned medical objects, such as livers and bones, to represent and visualize surgery cuts. The reconstructed surfaces will thereby be provided as triangular meshes and are often referred to as surface meshes. By construction, initially chosen curves on these surfaces are jagged due to the finite precision of the underlying mesh and omit curvature noise that is not neglectable and perceivable by the human eye. Hence, a smoothing process is applied to initial curves to reduce their overall curvature and attain surface cuts with well-defined properties. For medical surface cutting applications, though, the shape of an initial curve is defined by domain experts, such as physicians or bioengineers, and most likely indicates relevant anatomical landmarks or surface regions. Thus, under these circumstances, the smoothing additionally requires the resulting curve to be close to its original such that no essential information is lost during the process. (Alirr and Abd. Rahni 2019; Lawonn et al. 2014; Zachow et al. 2003)[1]

It is a matter of fact, that curves on surface meshes and algorithms for smoothing them are furthermore basic building blocks for mesh processing and segmentation (Ji et al. 2006; Kaplansky and Tal 2009). Consequently, their fundamental role in the areas of computer-aided geometric design, computer graphics, and visualization, that are heavily based on mesh processing, is unconcealable. So, curve smoothing on surface meshes is not only relevant in specific areas of medicine but is a generally applicable and important tool to many other domains of applications building on the above named research areas. Further application domains, such as machine learning (Benhabiles et al. 2011; Park et al. 2019) and engineering, that make use of the tools named above, provide many more direct and important applications.

[1] In this thesis, citations concerning a whole paragraph will be given after the last sentence of the very paragraph.

2 Preliminaries

Differential Geometry on Polyhedral Surfaces (Polthier and Schmies 2006)

Curvature Estimation on Surfaces (Rusinkiewicz 2004)

Generation of Surface Normals (Jin, Lewis, and West 2005; Max 1999; Meyer et al. 2001)

3 Previous Work

Application of Cutting Curves in Mesh Processing (Zachow et al. 2003) (Benhabiles et al. 2011) (Ji et al. 2006)

Previous Intuitive Approach called Corner Cutting in Planar (Chaikin 1974) (Dyn, Levin, and Liu 1992) in space (Morera, Velho, and Carvalho 2008) But this may not provide a real surface curve.

Lines as Snakes (Kass, Witkin, and Terzopoulos 1988) Generalization 2D-Manifold (Bischoff, Weyand, and Kobbelt 2005) (Jung and Kim 2004)

Automatic Surface Segmentation and Cutting (Lee and Lee 2002) (Lee et al. 2004)

Feature-Sensitive Curve Smoothing (Lai et al. 2007)

Geodesics on Triangular Meshes (Martínez, Velho, and Carvalho 2005)

Bezier Curves on Meshes (Martínez, Carvalho, and Velho 2007) and splines in manifolds (Hofer and Pottmann 2004) and geodesics in polyhedral surfaces (Polthier and Schmies 2006) (Mitchell, Mount, and Papadimitriou 1987) (Surazhsky et al. 2005)

geodesic distance fields (Bommes and Kobbelt 2007) (Kimmel and Sethian 1996)

heat maps (Crane, Weischedel, and Wardetzky 2013)

(Dijkstra 1959)

(Ma and Chen 2007) (Pottmann and Hofer 2005) (Lévy et al. 2002)

(Mancinelli et al. 2022)

(Yu, Schumacher, and Crane 2021)

(Engelke et al. 2018)

4 Implementation

5 Evaluation and Results

6 Conclusions and Future Work

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A Mathematical Proofs

B Further Code

Statutory Declaration

I declare that I have developed and written the enclosed Master's thesis completely by myself, and have not used sources or means without declaration in the text. Any thoughts from others or literal quotations are clearly marked. The Master's thesis was not used in the same or in a similar version to achieve an academic grading or is being published elsewhere.
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Bergen, November 17, 2022

Markus Pawellek