

Spatial Data Representations for Rapid Visualization and Analysis

A Dissertation Presented

by

LORI LYNNE LEMANCZYK SCARLATOS

to

The Graduate School

in Partial Fulfillment of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

in

COMPUTER SCIENCE

STATE UNIVERSITY OF NEW YORK

AT STONY BROOK

August 1993

Copyright by
Lori Lynne Lemanczyk Scarlatos
1993

Abstract of the Dissertation

**Spatial Data Representations
for Rapid Visualization and Analysis**

by

Lori Lynne Lemanczyk Scarlatos

Doctor of Philosophy

in

Computer Science

State University of New York

at Stony Brook

1993

Spatial data representations help to describe the world that we live in. Inherent characteristics of spatial data — multi-dimensionality and typically large volumes — make the representation of this information an interesting problem. As spatial data play ever greater roles in time-critical applications, demands on the data representations also increase.

The work described in this dissertation addresses three current problems with spatial data representations. First is the need for data representations that support multiple scales and precisions without losing critical information. Second is a requirement for spatial operations to exploit filtering techniques to improve performance. Third is a desire for merging techniques that will allow different data representations to exist separately yet work together so that different data representations may be used to their best advantage.

Three triangulation methods are presented. An adaptive hierarchical triangulation algorithm generates a structure with fixed levels of detail with a specified accuracy. The tree structure of this triangulation hierarchy supports pruning and filtering, and is therefore the basis of the manipulation algorithms described in the remaining chapters. Another method, curvature equalization, improves existing triangulations by ensuring that smooth areas are represented by relatively few triangles, and rough areas are represented by many more. This method is used to produce a good initial tessellation for the adaptive hierarchical triangulation. A distinguishing characteristic of all three methods is that they attempt to generalize critical lines on the surface with the triangle edges.

Algorithms for three spatial operations exploiting the adaptive hierarchical triangulation's tree structure are given. These operations — zoom, multi-resolution viewing, and line of sight calculation — represent typical time-critical visualization and analysis applications.

Techniques for merging the adaptive hierarchical triangulation with other data representations are described. These, too, exploit tree structures to improve performance of the merging algorithms. A significant contribution here is the polygonal line sweep, which can find all triangles inside an area without having to examine them all.

Table of Contents

List of Figures	vii
List of Tables	xi
Acknowledgements	xii
1. Introduction	1
1.1. Issues	2
1.2. Historical Perspective.....	6
1.3. Thesis overview	8
2. 3D Surface Representations	9
2.1. Sources of surface data.....	10
2.2. Critical surface features.....	13
2.3. Criteria for judging surface models.....	15
2.4. Surface tessellations	21
3. Triangulation hierarchies using cartographic coherence	32
3.1. Refined triangulation hierarchy.....	33
3.2. Adaptive hierarchical triangulation.....	43
4. Improving triangulations with curvature equalization	70
4.1. Foundations.....	71
4.2. Approach	75

4.3. Results	84
5. Spatial data manipulation.....	95
5.1. Benefits of spatial filtering.....	95
5.2. Zoom	96
5.3. Multi-resolution views	99
5.4. Line-of-sight.....	102
6. Merging spatial data representations	105
6.1. Background	107
6.2. Raster/TIN	113
6.3. Point	117
6.4. Line	123
6.5. Area	127
7. Conclusion	132
6.1. Curvature equalization for geometric modeling.....	133
6.2. Surface fitting with conics.....	134
6.3. Criteria for judging surface models.....	135
6.4. Dynamic terrain.....	144
6.5. Database integration.....	145
References	146

List of Figures

2.1. Delaunay triangulation of surfaces can introduce artificial features, like this artificial bridge over a ravine	25
2.2. Coarse sampling rates can cause features to shift or disappear.....	27
2.3. Simply splitting a triangles at its point of greatest error — and ignoring surface coherence — can produce poor approximations	29
2.4. Quadtree models are dependent on the orientation of the frame.....	30
3.1. Hypsoshading reveals coherence of cartographic features.....	32
3.2. Building the refined triangulation hierarchy	36
3.3. A star polygon is the union of all triangles that share vertex v	37
3.4. A corner point does not form the centroid of a star polygon	37
3.5. Re-triangulation approximates critical lines.....	38
3.6. Original digital elevation model with 130,050 triangles.....	40
3.7. Three levels of detail from a refined triangulation hierarchy with approximately 10000, 5000, and 2500 triangles (top to bottom)	41
3.8. Three levels of detail from subsampled grid with approximately 10000, 5000, and 2500 triangles (top to bottom)	41
3.9. Triangle splitting strategies	46
3.10. Some slivers in the model are inevitable.....	47

3.11. Adaptive grid structure for irregular data	49
3.12. Allowing edges to bend, to avoid unnecessary slivery triangles.....	51
3.13. Adaptive hierarchical triangulation.....	52
3.14. Measuring errors at the points.....	54
3.15. Split triangle at all 3 edges	56
3.16. Very long and thin triangles can cause anomalies that must be handled spe- cially by the triangulation algorithm.	57
3.17. Split long,thin triangles	57
3.18. Perspective view of AOI 7 represented by (a) original digital elevation model, (b) DeFloriani et al's hierarchical structure, and (c) adaptive hierar- chical triangulation.....	67
3.19. Long shot of AOI 7 represented by (a) original digital elevation model, (b) DeFloriani et al's hierarchical structure, and (c) adaptive hierarchical trian- gulation	68
4.1. Improving linear approximations with a split-and-merge technique	72
4.2. Split-and-merge analogy for a surface	73
4.3. Gaussian curvature alone will not detect all critical features, such as this edge of a cliff.....	74
4.4. Collapsing very thin triangles.....	78
4.5. Curvature of a surface model cannot always be truly equalized.....	79
4.6. Algorithm for equalizing curvature.....	80
4.7. Triangulations with equalized curvature may still contain more surface patches than are necessary.....	81
4.8. Algorithm for eliminating unnecessary triangles.....	82

4.9. Motivation for switching edge directions: slivery triangles (a) can be made less slivery (b)	82
4.10. Algorithm for switching edge directions.....	83
4.11. Curvature equalization applied to artificial test cases.....	84
4.12. AOI 6 modeled with (a) original digital elevation model, (b) adaptive hierarchical triangulation developed from AOI split in half, (c) curvature equalization applied to (b), and (d) adaptive hierarchical triangulation developed from curvature equalized initial triangulation.....	87
4.13. AOI 1 modeled with (a) original digital elevation model, (b) adaptive hierarchical triangulation developed from AOI split in half, and (c) adaptive hierarchical triangulation developed from curvature equalized initial triangulation	88
4.14. AOI 1 modeled with (a) original digital elevation model, (b) subsampled regular grid, and (c) curvature equalized subsampled grid	90
4.15. AOI 2 modeled with (a) original digital elevation model, (b) subsampled regular grid, and (c) curvature equalized subsampled grid	91
4.16. AOI 6 modeled with (a) original digital elevation model, (b) subsampled regular grid, and (c) curvature equalized subsampled grid	92
4.17. Window over a ridge of height h at two different orientations	94
5.1. Example of zoom.....	97
5.2. Algorithm for zoom.....	98
5.3. Algorithm for producing multi-resolution bull's-eye model.....	100
5.4. Multi-resolution model for bull's-eye viewing	101
5.5. Line of sight problem.....	102
5.6. Line of sight algorithm.....	104

6.1. A topological line sweep bends to discover one intersection at a time.....	115
6.2. Point indexing strategy.....	119
6.3. Using the determinant form reveals whether a point is inside a triangle and, if not, which neighbor to search next	121
6.4. In a multi-scale line tree, the error e at each level of detail defines a polygon that wholly contains the portion of the line being generalized.....	124
6.5. Interior triangles are found with a polygonal line sweep.....	128
6.6. Segmenting the polygonal sweep line.....	129

List of Tables

2.1	Indications of Gaussian (K) and mean (H) curvature.....	13
3.1.	Average error: refined triangulation hierarchy vs. subsampled grid.....	42
3.2.	Maximum error: refined triangulation hierarchy vs. subsampled grid.....	42
3.3.	Measures of sliveriness, values normalized to 1 for an equilateral triangle	63
3.4.	Comparison of hierarchies.....	64
3.5.	Total number of triangles in the hierarchy	65
3.6.	Number of triangles in the finest level of detail (error tolerance = 10m) ..	66
4.1.	Effects of the initial triangulation on sliveriness.....	86
4.2.	Effects of the initial triangulation on number of triangles in finest level of detail	86
4.3.	Effects of equalizing curvature of subsampled digital elevation models....	89

Acknowledgements

First, I wish to thank my advisor, Theo Pavlidis, who taught me what it means to do important research. He has been a great source of knowledge and inspiration for me. I never cease to learn from his example.

I am forever indebted to Herb Tesser. Over the years he has been a great teacher, advisor, mentor, boss, and friend. Without his influence, I never would have written this dissertation.

Many thanks to Geoffrey Gardner, who encouraged me to write my first conference paper. He, too, is a great friend, source of inspiration, and role model.

I am grateful to Rob Kelly for encouraging me to pursue the PhD while working in his department; and to Jay Mendelsohn for making me welcome in his lab and getting me started on the triangulation models.

Heartfelt thanks go out to my many other friends, colleagues and teachers who have offered me encouragement, ideas, knowledge, advice, and inspiration. Among these are Anita Beadon, Steve Cento, Keith Clarke, Venkat Devarjaram, David Eames, Jay Fiacco, Arie Kaufman, John Litke, Joe Mitchell, Bill Sakoda, Hanen Samet, Mike Sieverding, Steve Skiena, Dave Southard, Paul Taub, Tom Triscari, and Bill Verts.

On a personal note, I want to thank my family for all of their encouragement. I especially commend my dad for persistently cutting out all those computer graphics articles for me. I thank Loriann and Mark Cody for moral and technical support; and Terri and Chris and Anne and Phil for their hospitality during my years at NYU. Thanks are also due to my many other wonderful friends who,

with their jam sessions and other diversions, kept me sane.

My fellow students at Stony Brook will always hold a special place in my heart. Together we studied, shot pool, and helped each other over the hurdles of graduate school. Their comraderie made my years at Stony Brook all the more enjoyable.

Most of all, I want to thank my husband, Tony. Through thick and thin he's always stood by me. I couldn't have done it without him.

To all the others who have touched my life, yet are not listed here, I thank you, too. I am no less grateful.

Finally, I thank God.