

The Medial Scaffold for 3D Shape Modeling and Recognition

by

Ming-Ching Chang

B. S., National Taiwan University, Taipei, Taiwan, 1996

M. S., National Taiwan University, Taipei, Taiwan, 1998

A dissertation submitted in partial fulfillment of the
requirements for the Degree of Doctor of Philosophy
in the Division of Engineering at Brown University

Providence, Rhode Island

October 2008

© Copyright 2008 by Ming-Ching Chang

This dissertation by Ming-Ching Chang is accepted in its present form by the Department of Engineering as satisfying the dissertation requirement for the degree of Doctor of Philosophy.

Date _____

Benjamin B. Kimia, Director
Division of Engineering

Recommended to the Graduate Council

Date _____

Gabriel Taubin, Reader
Division of Engineering

Date _____

Frederic Fol Leymarie, Reader
Department of Computing, Goldsmiths College, University of London, UK

Approved by the Graduate Council

Date _____

Sheila Bonde
Dean of the Graduate School

Curriculum Vitae

Ming-Ching Chang was born on the 22nd of June, 1974, in Chung-Li, Taiwan. From 1989 to 1992, he attended the Taipei Municipal Chien-Kuo High School, the most prestigious high school in Taiwan. For his undergraduate education, he attended the National Taiwan University (NTU) in Taipei, where he majored in Civil Engineering. He is interested in computer programming and published a book on object-oriented programming in C++ in 1994. In 1996, He attended the Graduate School of Computer Science and Information Engineering at NTU and graduated with a M.S. degree in 1998. Simultaneously, he worked as a research assistant on several automatic visual inspection and pattern identification projects in the Mechanical Industry Research Laboratories department within the Industrial Technology Research Institute (ITRI), the leading national research organization in Hsin-Chu, Taiwan. Then, he worked as a full-time teaching assistant in the Computer Center at the College of Management in NTU. Since 2001, he has been working at the Laboratory for Engineering Man/Machine Systems (LEMS) in the Division of Engineering at Brown University. Though he has primarily been working on 3D shape modeling and recognition problems at LEMS as a research assistant, he has also been a teaching assistant for a number of graduate and undergraduate courses in computer vision. Additionally, he has published several papers in leading national and international conferences in computer vision and graphics. His research interests include computer vision and medical imaging, mainly in the topics of shape representation, modeling, visualization, registration, and recognition.

Acknowledgements

First and foremost, I would like to thank my parents, Sheng-Chu Chang and Lan-Teng Yu, to whom I dedicate this thesis, for their infinite love and support through the thirty years of my life as a student. From very early on, they encouraged me to set high goals and to strive to reach them. I owe it to them for instilling in me the desire to be all I can be. I would also like to thank my grandfather, grandmother, aunts and uncles, brother, and cousins. My positive personality traits are products of your love; I am very lucky to have been born into such a lovely family.

Next, I would like to thank my advisor, Prof. Benjamin Kimia, for his continual guidance and support throughout the years of my graduate study. I will especially cherish the one-on-one meetings where he made me “think abstractly” and “communicate effectively” while journeying through the realm of research. Above all, I am grateful for all the insight he gave me, my favorite being to see and think through all the problems that I could encounter in my life and to find a way out before the fact.

I would also like to thank Prof. Gabriel Taubin, Prof. Joseph Mundy, and Prof. David Cooper for their advice, guidance, and for their stimulating classes. I would like to thank them for providing valuable comments about my research, being on my progress review committee, and being on my thesis committee. I would especially like to thank Prof. Frederic Fol Leymarie as a mentor and a friend, who provided an immense amount of helpful guidance regarding my research in addition to being on my thesis committee.

Next I would like to thank all my colleagues at LEMS, Thomas and Amir, for their kindness and friendship from the first day I arrived at Brown, Andrew, Kong-bin, Dongjin, Vishal, John, Ozge, Matt, Dan, Nhon, Ricardo, Yong, Shubao, Ibo, Can, Doug, Eduardo, Isa, Fatih, and everyone else in the group, for making the journey interesting and fun. I am grateful for all the stimulating discussions, the friendship and social interactions, and the enriching international culture.

Next, I would like to thank the Taiwanese community at Brown, especially Mei-Hsiu and Peter, Chun-Chia and Phoebe, Ping, and everyone else, who embraced me with open arms since my first day at Brown. I would especially like to thank Roger, Chih-Hsun and Chia-Hsuan, Chia-En, Tai-Sen, Doug, Feng-Hao, Ming-Li, Lenora, Eunice, and everyone else, who declared me as their “godfather” and who created a community, a home away from home at Brown. Lastly, I would like to thank my house-mate, Sirod, for his friendship and help since the beginning of my stay.

Finally I would like to thank my wife, Yu-Ju, for her undivided love throughout all these years and for her continual encouragement and support. I would especially like to thank her for leaving home half a world away to start a new life with me, and for the years of commuting to and from work in order to spend every sweet night with me. I owe her everything and hope to reciprocate her devotion to me for the rest of my life.

Abstract

In this thesis, we develop the *medial scaffold* (\mathcal{MS}) technology, a graph-based medial axis (\mathcal{MA}) representation, which is applied to model 3D shapes in a range of applications and lead toward the ultimate goal of recognition. The \mathcal{MA} is with great promise as a universal model for shape, since it outlines many features explicitly in a hierarchy and allows to organize them completely (enabling an exact reconstruction). A key issue in using the 3D \mathcal{MA} is that, how the complex \mathcal{MA} structure can be regularized so that similar, within-category 3D shapes yield similar 3D \mathcal{MA} that are distinct from the non-category shapes. My work extends a line of research which (i) organizes the 3D \mathcal{MA} into a hierarchical hypergraph by studying its singularity typology, and (ii) classifies the instabilities of the \mathcal{MA} structure, or *transitions* (sudden topological changes due to a small perturbation). A set of \mathcal{MS} *transforms* is defined in a case-by-case analysis to model the \mathcal{MS} across all generic transitions, thus allows manipulating the underlying shape and regularizing it toward a near-by degenerate transition point. The simplified \mathcal{MS} preserves with-in-category similarity, thus enables various applications including shape analysis, robust feature detection, and manipulation. It is also useful in establishing a similarity measure in matching shapes, by adopting a graph matching scheme for the \mathcal{MS} hypergraph. Results of the proposed framework demonstrate its state-of-art in \mathcal{MA} -based modeling and promises its potential in shape-based matching.

Contents

1	Introduction	1
1.1	A Brief Overview of this Thesis	1
1.2	From Medial Axis to Medial Scaffold: Computation, Modeling, and Regularization	7
1.3	Matching 3D Shapes by Matching their Regularized Medial Scaffolds	12
1.4	Main Contributions	12
1.5	Organization of Thesis	14
2	Background on Medial Axis, Graph-based Representation and their Matching	16
2.1	Survey of 3D Shape Representation and Matching	16
2.2	Survey of the 3D Medial Axis Computation	18
2.2.1	Survey of Voronoi-filtering methods for \mathcal{MA} computation and surface meshing	20
2.3	Survey of the 3D Medial Axis Regularization	21
2.3.1	Remarks on related \mathcal{MA} regularization works	24
2.3.2	Survey of the 3D curve-like skeleton computation	27
2.4	Survey of Graph Matching for Recognition	29
3	A Review of the Medial Scaffold	32
3.1	Local Form of Shock Points: Contact with Spheres and Shock Flow Analysis	33
3.1.1	Contact typology of a shock point: the A_k^n notation	33
3.1.2	Flow typology of a shock point: the A_k^{n-l} notation	36
3.2	The Medial Scaffold (\mathcal{MS}) and Shock Scaffold (\mathcal{SC}) Hierarchies	37
3.3	\mathcal{MS} and \mathcal{SC} for a Point Set	40
3.3.1	Classification of the \mathcal{MS} sheets, curves, and vertices based on a radius flow analysis	40
3.3.2	Construction of the \mathcal{MS} from a Voronoi-based computation	44
3.4	Future Work: a Complete Flow Analysis of the \mathcal{MS} toward the \mathcal{SC}	47
4	Separating the Topology and Fine-Scale Geometry of the Medial Scaffold	49
4.1	The Dual-Scale Representation of the \mathcal{MS}	50
4.2	A Review of the Half-Edge (\mathcal{HE}) Data Structure to Represent Polyhedral Meshes	52
4.3	Extend the Half-Edge Data Structure to Represent General Non-Manifold Polyhedral Meshes	53
4.4	The Extended Half-Edge (\mathcal{EHE}) Data Structure to Represent the \mathcal{MS} Hypergraph	54

5	Medial Scaffold Transforms	58
5.1	A Review of Generic \mathcal{MA} Transitions and Corresponding \mathcal{MS} Transforms	59
5.2	Generic \mathcal{MS} Transforms for Simple Closed Shapes	62
5.2.1	Splice Type Transforms	62
5.2.2	Contract Type Transforms	65
5.2.3	Merge Type Transforms	71
5.3	\mathcal{MS} Transforms for Non-Closed Shapes	73
5.3.1	Gap Type Transforms	74
5.3.2	Loop Transform	75
5.4	Non-Generic Higher-Order \mathcal{MS} Transforms	75
5.4.1	Corner-merge transform	76
5.4.2	Higher-order merge transforms	77
5.5	Analysis of High-Order \mathcal{MS} Nodes and Curves	77
6	From Point Clouds to Surfaces: On Using the Medial Scaffold for Surface Meshing	80
6.1	Philosophy of the Proposed Surface Reconstruction Approach	80
6.2	The Shock Segregation (Meshing) Algorithm in Applying the Gap Transforms	83
6.3	Experimental Results	90
6.4	A Bucketing Technique for Handle Large Inputs	92
7	Medial Scaffold Regularization	98
7.1	Overview of the Computational Strategy for \mathcal{MS} Regularization	98
7.2	The Computational Pipeline for \mathcal{MS} Regularization	101
7.2.1	Splice regularization	103
7.2.2	Regularizing A_3 rib curves	103
7.2.3	(Optional) \mathcal{MS} component selection	105
7.2.4	Construct coarse-scale \mathcal{MS}	105
7.2.5	Iterative \mathcal{MS} regularization using all shock transforms	106
7.2.6	(Optional) smoothing A_3 rib curves	107
7.3	Maintaining a Consistent Boundary and \mathcal{MS} Association	107
7.4	Implementation and Experimental Results	109
8	On Edit-Distance Matching of the Medial Scaffolds	116
8.1	Main Difficulties of the \mathcal{MS} Hypergraphs Edit-Distance Matching and a Sub-optimal Solution	117
8.2	Deformation Cost to Match a Pair of A_1^2 Medial Sheets	121
8.3	Deformation Cost to Match a Pair of A_1^3 Medial Curves	123
8.4	Deformation Cost to Match a Pair of A_3 Medial Curves	126
8.5	Defining Deformation Costs for the \mathcal{MS} Transforms	127
9	3D Object Recognition by Graph-Based Matching of the Medial Scaffolds	128
9.1	A Reviews of the Graduated Assignment (\mathcal{GA}) Graph Matching Algorithm	129
9.2	On Extending the \mathcal{GA} to Match \mathcal{MS} Hypergraphs	131
9.3	Designing the \mathcal{MS} Hypergraph Compatibility Measures	133
9.3.1	The first-order <i>node</i> compatibility measure (\mathcal{N})	133
9.3.2	The second-order <i>link (curve)</i> compatibility measure (\mathcal{L})	137
9.3.3	The third-order <i>sheet (corner)</i> compatibility measure (\mathcal{C})	140

9.4	Virtual Links to Handle Remaining \mathcal{MS} Transitions	142
9.5	Computing the (Post-Matching) Similarity Measure	144
9.6	Summary and Experimental Results	146
10	Applications of the Regularized \mathcal{MS} Medial Scaffolds	153
10.1	A Survey of Shape Modeling and Matching Applications	153
10.2	Ridge Detection	158
10.3	Analysis of Mathematical Shapes	160
10.3.1	\mathcal{MA} around a smooth corner	160
10.3.2	Exterior \mathcal{MA} of a “torus knot”	161
10.3.3	\mathcal{MA} of the “Gomboc”	162
10.4	Global Registration by Matching the \mathcal{MS}	163
10.4.1	On computing an average shape (atlas)	164
11	Conclusions	167
11.1	Conclusive Remarks on Main Topics Covered in this Thesis	168
	Bibliography	171