

Contents

1	Introduction	1
1.1	Motivation	1
1.1.1	Segmentation of Medical Image Data	2
1.1.2	Automation of the Segmentation Task	4
1.1.3	Segmentation Accuracy	5
1.2	Scope of this Thesis	5
1.2.1	Automated Segmentation with Deformable Models	5
1.2.2	Selection of Anatomical Structures and Imaging Modalities	9
1.2.3	Contribution	9
1.2.4	Topics Not Discussed	11
1.3	Structure of this Thesis	12
Part I	The Segmentation Framework	15
2	Basic Terms and Notation	17
2.1	Images, Segmentations, and Surface Meshes	18
2.1.1	Three-dimensional Medical Images	18
2.1.2	Segmentations of Three-dimensional Medical Images	18
2.1.3	Triangle Surface Meshes	19
2.1.4	From Segmentations to Surface Meshes and Back	21
2.2	Deformable Surface Meshes	21
2.2.1	Displacement Fields and Sets of Candidate Displacements	22
2.2.2	Appearance Cost	22
3	Deformable Meshes for Automatic Segmentation	25
3.1	Statistical Shape Models (SSMs) for Segmentation	27
3.1.1	Generation of SSMs	28
3.1.2	Prerequisites: Shape Correspondences and Alignment	29
3.1.3	Image Segmentation via SSM Deformation	30
3.1.4	Initial Shape Detection	32
3.1.5	Lack of Image Features: SSMs for Extrapolation	33

3.2	A Simple Heuristic Appearance Model	34
3.2.1	Appearance Cost Function	34
3.2.2	Intensity Parameter Estimation	35
3.3	Local Search for Appearance Match	35
3.3.1	Unidirectional Displacements	35
3.3.2	Optimal Displacement Fields	36
3.3.3	Intensity Profiles	37
3.4	Shape-constrained Free Mesh Deformations	37
3.4.1	Free Deformation within a Narrow Band	39
3.4.2	Free Deformation with Bounded Displacement Differences	40
3.5	Simultaneous Free Deformations of Multiple Meshes	43
3.5.1	Multi-object Graph-based Deformation of Coupled Meshes	44
3.5.2	Coupling Adjacent Surface Meshes	45
3.6	Conclusion	49
4	Omnidirectional Displacements for Deformable Surfaces (ODDS)	51
4.1	The Visibility Problem	52
4.2	ODDS: Free Mesh Deformations with All-around Visibility	53
4.2.1	Omnidirectional Displacements	54
4.2.2	The Mesh Deformation Problem	55
4.2.3	Optimal Mesh Deformation via MRF Energy Minimization	56
4.2.4	Refined Regularization	56
4.2.5	Proof of Concept Synthetic Experiments	57
4.3	FastODDS	60
4.3.1	Where to use Omnidirectional Displacements	61
4.3.2	The Hybrid Mesh Deformation Problem	62
4.3.3	Optimal Hybrid Mesh Deformation	62
4.3.4	Multi-object FastODDS	64
4.3.5	Appendix: Automatic Ridge Detection	64
4.4	Conclusion	65
5	From Surface Mesh Deformations to Volume Deformations	67
5.1	Mesh-based Extrapolation	68
5.1.1	Introduction	68
5.1.2	Affine Transformations	70
5.1.3	Polyaffine Transformations	70
5.1.4	Mean Value Coordinates	72
5.2	Atlas-based Segmentation	73
5.2.1	Image-to-image Registration	74
5.2.2	Application of Volume Deformations to Atlases	76
5.3	Conclusion	76

Part II Applications to Medical Image Data	79
6 Fundamentals of Quantitative Evaluation	81
6.1 Measures of Segmentation Accuracy	82
6.2 Presentation of Results	84
6.3 Comparison of Methods	85
6.4 Generalization to New Image Data	86
6.5 Parameter Settings	86
7 Single-object Segmentation of Anatomical Structures	89
7.1 Segmentation of the Liver in Contrast-enhanced CT	91
7.1.1 Statistical Shape Model of the Liver	92
7.1.2 Application-specific Initialization	92
7.1.3 Heuristic Appearance Model for Displacement Computation .	92
7.1.4 Segmentation Pipeline	95
7.1.5 Results and Discussion	96
7.2 Segmentation of the Pelvic Bones in CT	100
7.2.1 Image Data and SSM of the Pelvic Bones	101
7.2.2 Segmentation Pipeline	102
7.2.3 Results and Discussion	102
7.3 Segmentation of the Mandibular Bone and Nerve in CBCT	108
7.3.1 Image Data and Compound SSM of Mandible and Nerves .	109
7.3.2 SSM-Based Reconstruction of Bone and Nerve	109
7.3.3 Image-based Refinement of Nerve Delineation	110
7.3.4 Results and Discussion	112
7.4 Conclusion	114
8 Multi-object Segmentation of Joints	117
8.1 Segmentation of the Hip Joint in CT Data	118
8.2 Segmentation of Knee Bones and Cartilage in MR Data	121
8.2.1 SSMs of Femur and Tibia and Cartilage Thickness Model .	122
8.2.2 Appearance Cost Functions and Parameter Estimation .	123
8.2.3 Multi-object Segmentation Pipeline	125
8.2.4 Results and Discussion	126
8.3 Conclusion	126
9 ODDS for Segmentation of Highly Curved Structures	131
9.1 Experimental Setup	132
9.1.1 Identification of the Mandibular Coronoid Process	133
9.1.2 Acetabular Rim Delineation on Surface Meshes	134
9.2 Results	135
9.2.1 Mandibular Coronoid Process	135

9.2.2	Acetabular Rim and Hip Bones	137
9.2.3	Run-time and Memory Requirements	138
9.3	Discussion	139
9.3.1	Segmentation Accuracy	139
9.3.2	Comparability of Regularization	141
9.3.3	Influence of Mesh Resolution	142
9.3.4	Consistency of Deformed Meshes	143
9.3.5	Run-time and Memory Requirements	144
9.4	Conclusion	145
10	Extrapolation and Atlas-based Segmentation of Leg Muscles	147
10.1	Extraction of Anatomical Landmarks of the Pelvic Bones	148
10.1.1	Methods	149
10.1.2	Results and Discussion	151
10.2	Segmentation of Leg Muscles	152
10.2.1	Segmentation Pipeline	154
10.2.2	Results and Discussion	156
10.3	Conclusion	159
Conclusions		161
Publications		163
Bibliography		165