# Contents

## 1 Introduction

1.1 Advances in Medical Imaging ........................................ 1
1.2 Applications of Automatic Detection and Segmentation in Medical Imaging ....................................................... 3
1.3 Previous Work on Automatic Object Detection in Medical Images ................................................................. 6
1.4 Previous Work on Medical Image Segmentation .................. 9
1.5 Marginal Space Learning ................................................. 11
1.6 Comparison of Marginal Space Learning and Full Space Learning for 2D Problems ........................................... 12
1.7 Constrained Marginal Space Learning ............................... 12
1.8 Marginal Space Learning for Nonrigid Object Detection ...... 14
1.8.1 Optimal Mean Shape .............................................. 14
1.8.2 Direct Estimation of Nonrigid Deformation Parameters ... 15
1.9 Other Extensions of Marginal Space Learning .................... 16
1.10 Nonrigid Object Segmentation ....................................... 17
1.11 Applications of Marginal Space Learning ........................ 18
1.12 Organization of this Book ............................................ 19
References ..................................................................... 19

## 2 Marginal Space Learning

2.1 Introduction .................................................................... 25
2.2 3D Object Detection Using Marginal Space Learning ........ 27
2.2.1 Derivation of Object Pose Ground Truth From Mesh ...... 27
2.2.2 Principle of Marginal Space Learning .......................... 29
2.2.3 Training of Position Estimator .................................... 32
2.2.4 Training of Position-Orientation Estimator .................. 34
2.2.5 Training of Position-Orientation-Scale Estimator .......... 35
2.2.6 Aggregation of Pose Candidates ............................... 36
2.2.7 Object Detection in Unseen Volume .......................... 36
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>3D Image Features</td>
<td>37</td>
</tr>
<tr>
<td>2.3.1</td>
<td>3D Haar Wavelet Features</td>
<td>38</td>
</tr>
<tr>
<td>2.3.2</td>
<td>Steerable Features</td>
<td>41</td>
</tr>
<tr>
<td>2.4</td>
<td>Classifiers</td>
<td>43</td>
</tr>
<tr>
<td>2.4.1</td>
<td>Probabilistic Boosting-Tree</td>
<td>44</td>
</tr>
<tr>
<td>2.4.2</td>
<td>Combining Classifier Cascade and Tree</td>
<td>47</td>
</tr>
<tr>
<td>2.5</td>
<td>Experiments on Heart Chamber Detection in CT Volumes</td>
<td>49</td>
</tr>
<tr>
<td>2.6</td>
<td>Direct Estimation of Nonrigid Deformation Parameters</td>
<td>54</td>
</tr>
<tr>
<td>2.6.1</td>
<td>Nonrigid Marginal Space Learning</td>
<td>54</td>
</tr>
<tr>
<td>2.6.2</td>
<td>Experiments on Liver Detection in 3D CT Volumes</td>
<td>56</td>
</tr>
<tr>
<td>2.7</td>
<td>Theoretical Foundations of Marginal Space Learning</td>
<td>58</td>
</tr>
<tr>
<td>2.7.1</td>
<td>Relation to Shortest Path Computation</td>
<td>58</td>
</tr>
<tr>
<td>2.7.2</td>
<td>Relation to Particle Filtering</td>
<td>63</td>
</tr>
<tr>
<td>2.8</td>
<td>Conclusions</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>63</td>
</tr>
<tr>
<td>3</td>
<td>Comparison of Marginal Space Learning and Full Space Learning in 2D</td>
<td>67</td>
</tr>
<tr>
<td>3.1</td>
<td>Introduction</td>
<td>67</td>
</tr>
<tr>
<td>3.2</td>
<td>Marginal Space Learning for 2D Object Detection</td>
<td>68</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Training of Position Estimator</td>
<td>70</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Training of Position-Orientation Estimator</td>
<td>70</td>
</tr>
<tr>
<td>3.2.3</td>
<td>Training of Position-Orientation-Scale Estimator</td>
<td>71</td>
</tr>
<tr>
<td>3.2.4</td>
<td>Object Detection in Unseen Images</td>
<td>72</td>
</tr>
<tr>
<td>3.3</td>
<td>Full Space Learning for 2D Object Detection</td>
<td>72</td>
</tr>
<tr>
<td>3.4</td>
<td>Performance Comparison Experiment for MSL and FSL Detection</td>
<td>74</td>
</tr>
<tr>
<td>3.5</td>
<td>Conclusions</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>77</td>
</tr>
<tr>
<td>4</td>
<td>Constrained Marginal Space Learning</td>
<td>79</td>
</tr>
<tr>
<td>4.1</td>
<td>Introduction</td>
<td>79</td>
</tr>
<tr>
<td>4.2</td>
<td>3D Orientation</td>
<td>80</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Representation with Euler Angles</td>
<td>81</td>
</tr>
<tr>
<td>4.2.2</td>
<td>Representation with Quaternions</td>
<td>83</td>
</tr>
<tr>
<td>4.2.3</td>
<td>Uniform Sampling of 3D Orientation Space</td>
<td>85</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Mean Orientation</td>
<td>86</td>
</tr>
<tr>
<td>4.3</td>
<td>Constrained Search Space for MSL</td>
<td>87</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Constrained Space for Object Position</td>
<td>87</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Constrained Space for Orientation</td>
<td>89</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Constrained Space for Scale</td>
<td>91</td>
</tr>
<tr>
<td>4.4</td>
<td>Experiments on Constrained Marginal Space Learning</td>
<td>93</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Liver Detection in CT Volumes</td>
<td>93</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Left Ventricle Detection in CT Volumes</td>
<td>95</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Left Ventricle Detection in Ultrasound Volumes</td>
<td>98</td>
</tr>
</tbody>
</table>
## 5 Part-Based Object Detection and Segmentation

### 5.1 Introduction

### 5.2 Part-Based Left Atrium Detection and Segmentation in C-arm CT

- **5.2.1 Part-Based Left Atrium Model** ........................................... 107
- **5.2.2 Constrained Detection of Left Atrium Parts** ...................... 109
- **5.2.3 Experiments on Left Atrium Segmentation in C-arm CT** ........ 111

### 5.3 Ranking Based Multi-Detector Aggregation for Left Ventricle Detection in 2D MRI

- **5.3.1 Part-Based Left Ventricle Model** ................................. 116
- **5.3.2 Ranking Features** .................................................. 117
- **5.3.3 Ranking-Based Aggregation** ...................................... 121
- **5.3.4 Experiments on Ranking-Based Aggregation** .................. 122

### 5.4 Part-Based Aorta Detection and Segmentation from C-arm CT

- **5.4.1 Part-Based Aorta Segmentation** ................................. 125
- **5.4.2 Evaluation of Aorta Segmentation** .............................. 131

### 5.5 Conclusions

### References

## 6 Optimal Mean Shape for Nonrigid Object Detection and Segmentation

### 6.1 Introduction

### 6.2 Heuristic Mean Shape Using a Bounding Box Based Approach

### 6.3 Optimal Mean Shape for Nonrigid Shape Initialization

- **6.3.1 Procrustes Optimization for Mean Shape and Pose Parameters** ........................................... 139
- **6.3.2 Procrustes Analysis Under Isotropic Similarity Transformation** ........................................... 140
- **6.3.3 Procrustes Analysis Under Anisotropic Similarity Transformation** ........................................... 142
- **6.3.4 Generalized Procrustes Analysis to Align a Group of Shapes Under Anisotropic Similarity Transformation** ........................................... 144

### 6.4 Application to Aortic Valve Landmark Detection

- **6.4.1 Aortic Valve Landmark Detection for Transcatheter Aortic Valve Implantation** ............... 146
- **6.4.2 Unique Mean Shape for Aortic Valve Landmarks** .............. 147
- **6.4.3 Experiments on Aortic Valve Landmark Detection** .......... 148

### 6.5 Application to Whole-Heart Segmentation

- **6.5.1 Whole-Heart Segmentation** ...................................... 150
- **6.5.2 Experiments on Whole-Heart Segmentation** .................. 153

### References
6.6 Conclusions ............................................................ 156
References ..................................................................... 156

7 Nonrigid Object Segmentation: Application
to Four-Chamber Heart Segmentation ................................. 159
7.1 Introduction ............................................................ 159
7.2 Related Work on Heart Modeling and Segmentation .......... 161
  7.2.1 Heart Modeling ...................................................... 161
  7.2.2 Heart Segmentation ............................................. 162
7.3 Four-Chamber Heart Modeling ....................................... 162
  7.3.1 Left Ventricle and Left Atrium Models ..................... 162
  7.3.2 Right Ventricle and Right Atrium Models .................. 163
  7.3.3 Establishing Point Correspondence ......................... 166
  7.3.4 Statistical Shape Model ...................................... 168
7.4 Nonrigid Deformation Estimation for Heart Chambers .......... 173
  7.4.1 Learning Based Boundary Detector ......................... 174
  7.4.2 TPS Deformation Model ...................................... 175
  7.4.3 Boundary Delineation ........................................ 177
7.5 Optimal Smooth Surface for Left Ventricle Endocardium	
  Segmentation .............................................................. 179
  7.5.1 Clinical Requirements ......................................... 179
  7.5.2 Left Ventricle Blood Pool Extraction ....................... 181
  7.5.3 Optimization Based Surface Smoothing .................... 182
  7.5.4 Comparison with Previous Work ............................ 185
7.6 Experiments on Four-Chamber Heart Segmentation .......... 186
  7.6.1 Data Sets .......................................................... 186
  7.6.2 Experiments on Boundary Delineation ...................... 187
  7.6.3 Heart Chamber Tracking ..................................... 193
7.7 Conclusions ............................................................ 195
References ..................................................................... 196

8 Applications of Marginal Space Learning in Medical Imaging .... 199
8.1 Introduction ............................................................ 199
8.2 Detection of Devices and Anatomical Structures .............. 200
  8.2.1 Ultrasound Transducer Detection in Fluoroscopy ........ 200
  8.2.2 Balloon Marker Detection in Fluoroscopy  
      for Stent Enhancement ........................................... 201
  8.2.3 Pigtail Catheter Tip Detection in Fluoroscopy ............ 203
  8.2.4 Catheter Detection and Tracking in Fluoroscopy ........ 204
  8.2.5 Landmark Detection and Scan Range  
      Delimitation in Topogram ..................................... 205
  8.2.6 Left and Right Ventricle Detection in 2D MRI .......... 207
  8.2.7 Cardiac Measurements from 2D Ultrasound .............. 210
  8.2.8 Mid-Sagittal Plane Detection in 3D MRI ................... 211
  8.2.9 Intervertebral Disk Detection in 3D MRI/CT .......... 212
  8.2.10 Osteolytic Spinal Bone Lesion Detection in CT ......... 214
Marginal Space Learning for Medical Image Analysis
Efficient Detection and Segmentation of Anatomical Structures
Zheng, Y.; Comaniciu, D.
2014, XX, 268 p. 122 illus., 58 illus. in color., Hardcover
ISBN: 978-1-4939-0599-7