

# Contents

<b>Preface</b>	<b>ix</b>
<b>1 Introduction</b>	<b>1</b>
1.1 What is computer vision? . . . . .	3
1.2 A brief history . . . . .	10
1.3 Book overview . . . . .	17
1.4 Sample syllabus . . . . .	23
1.5 A note on notation . . . . .	25
1.6 Additional reading . . . . .	25
<b>2 Image formation</b>	<b>27</b>
2.1 Geometric primitives and transformations . . . . .	29
2.1.1 Geometric primitives . . . . .	29
2.1.2 2D transformations . . . . .	33
2.1.3 3D transformations . . . . .	36
2.1.4 3D rotations . . . . .	37
2.1.5 3D to 2D projections . . . . .	42
2.1.6 Lens distortions . . . . .	52
2.2 Photometric image formation . . . . .	54
2.2.1 Lighting . . . . .	54
2.2.2 Reflectance and shading . . . . .	55
2.2.3 Optics . . . . .	61
2.3 The digital camera . . . . .	65
2.3.1 Sampling and aliasing . . . . .	69
2.3.2 Color . . . . .	71
2.3.3 Compression . . . . .	80
2.4 Additional reading . . . . .	82
2.5 Exercises . . . . .	82
<b>3 Image processing</b>	<b>87</b>
3.1 Point operators . . . . .	89
3.1.1 Pixel transforms . . . . .	91
3.1.2 Color transforms . . . . .	92
3.1.3 Compositing and matting . . . . .	92
3.1.4 Histogram equalization . . . . .	94

## Contents

3.1.5	<i>Application: Tonal adjustment</i>	97
3.2	Linear filtering	98
3.2.1	Separable filtering	102
3.2.2	Examples of linear filtering	103
3.2.3	Band-pass and steerable filters	104
3.3	More neighborhood operators	108
3.3.1	Non-linear filtering	108
3.3.2	Morphology	112
3.3.3	Distance transforms	113
3.3.4	Connected components	115
3.4	Fourier transforms	116
3.4.1	Fourier transform pairs	119
3.4.2	Two-dimensional Fourier transforms	123
3.4.3	Wiener filtering	123
3.4.4	<i>Application: Sharpening, blur, and noise removal</i>	126
3.5	Pyramids and wavelets	127
3.5.1	Interpolation	127
3.5.2	Decimation	130
3.5.3	Multi-resolution representations	132
3.5.4	Wavelets	136
3.5.5	<i>Application: Image blending</i>	140
3.6	Geometric transformations	143
3.6.1	Parametric transformations	145
3.6.2	Mesh-based warping	149
3.6.3	<i>Application: Feature-based morphing</i>	152
3.7	Global optimization	153
3.7.1	Regularization	154
3.7.2	Markov random fields	158
3.7.3	<i>Application: Image restoration</i>	169
3.8	Additional reading	169
3.9	Exercises	171
<b>4</b>	<b>Feature detection and matching</b>	<b>181</b>
4.1	Points and patches	183
4.1.1	Feature detectors	185
4.1.2	Feature descriptors	196
4.1.3	Feature matching	200
4.1.4	Feature tracking	207
4.1.5	<i>Application: Performance-driven animation</i>	209
4.2	Edges	210
4.2.1	Edge detection	210
4.2.2	Edge linking	215
4.2.3	<i>Application: Edge editing and enhancement</i>	219
4.3	Lines	220
4.3.1	Successive approximation	220
4.3.2	Hough transforms	221

## Contents

4.3.3	Vanishing points . . . . .	224
4.3.4	<i>Application</i> : Rectangle detection . . . . .	226
4.4	Additional reading . . . . .	227
4.5	Exercises . . . . .	228
<b>5</b>	<b>Segmentation</b> . . . . .	<b>235</b>
5.1	Active contours . . . . .	237
5.1.1	Snakes . . . . .	238
5.1.2	Dynamic snakes and CONDENSATION . . . . .	243
5.1.3	Scissors . . . . .	246
5.1.4	Level Sets . . . . .	248
5.1.5	<i>Application</i> : Contour tracking and rotoscoping . . . . .	249
5.2	Split and merge . . . . .	250
5.2.1	Watershed . . . . .	251
5.2.2	Region splitting (divisive clustering) . . . . .	251
5.2.3	Region merging (agglomerative clustering) . . . . .	251
5.2.4	Graph-based segmentation . . . . .	252
5.2.5	Probabilistic aggregation . . . . .	253
5.3	Mean shift and mode finding . . . . .	254
5.3.1	K-means and mixtures of Gaussians . . . . .	256
5.3.2	Mean shift . . . . .	257
5.4	Normalized cuts . . . . .	260
5.5	Graph cuts and energy-based methods . . . . .	264
5.5.1	<i>Application</i> : Medical image segmentation . . . . .	268
5.6	Additional reading . . . . .	268
5.7	Exercises . . . . .	270
<b>6</b>	<b>Feature-based alignment</b> . . . . .	<b>273</b>
6.1	2D and 3D feature-based alignment . . . . .	275
6.1.1	2D alignment using least squares . . . . .	275
6.1.2	<i>Application</i> : Panography . . . . .	277
6.1.3	Iterative algorithms . . . . .	278
6.1.4	Robust least squares and RANSAC . . . . .	281
6.1.5	3D alignment . . . . .	283
6.2	Pose estimation . . . . .	284
6.2.1	Linear algorithms . . . . .	284
6.2.2	Iterative algorithms . . . . .	286
6.2.3	<i>Application</i> : Augmented reality . . . . .	287
6.3	Geometric intrinsic calibration . . . . .	288
6.3.1	Calibration patterns . . . . .	289
6.3.2	Vanishing points . . . . .	290
6.3.3	<i>Application</i> : Single view metrology . . . . .	292
6.3.4	Rotational motion . . . . .	293
6.3.5	Radial distortion . . . . .	295
6.4	Additional reading . . . . .	296
6.5	Exercises . . . . .	296

<b>7</b>	<b>Structure from motion</b>	<b>303</b>
7.1	Triangulation . . . . .	305
7.2	Two-frame structure from motion . . . . .	307
7.2.1	Projective (uncalibrated) reconstruction . . . . .	312
7.2.2	Self-calibration . . . . .	313
7.2.3	<i>Application: View morphing</i> . . . . .	315
7.3	Factorization . . . . .	315
7.3.1	Perspective and projective factorization . . . . .	318
7.3.2	<i>Application: Sparse 3D model extraction</i> . . . . .	319
7.4	Bundle adjustment . . . . .	320
7.4.1	Exploiting sparsity . . . . .	322
7.4.2	<i>Application: Match move and augmented reality</i> . . . . .	324
7.4.3	Uncertainty and ambiguities . . . . .	326
7.4.4	<i>Application: Reconstruction from Internet photos</i> . . . . .	327
7.5	Constrained structure and motion . . . . .	329
7.5.1	Line-based techniques . . . . .	330
7.5.2	Plane-based techniques . . . . .	331
7.6	Additional reading . . . . .	332
7.7	Exercises . . . . .	332
<b>8</b>	<b>Dense motion estimation</b>	<b>335</b>
8.1	Translational alignment . . . . .	337
8.1.1	Hierarchical motion estimation . . . . .	341
8.1.2	Fourier-based alignment . . . . .	341
8.1.3	Incremental refinement . . . . .	345
8.2	Parametric motion . . . . .	350
8.2.1	<i>Application: Video stabilization</i> . . . . .	354
8.2.2	Learned motion models . . . . .	354
8.3	Spline-based motion . . . . .	355
8.3.1	<i>Application: Medical image registration</i> . . . . .	358
8.4	Optical flow . . . . .	360
8.4.1	Multi-frame motion estimation . . . . .	363
8.4.2	<i>Application: Video denoising</i> . . . . .	364
8.4.3	<i>Application: De-interlacing</i> . . . . .	364
8.5	Layered motion . . . . .	365
8.5.1	<i>Application: Frame interpolation</i> . . . . .	368
8.5.2	Transparent layers and reflections . . . . .	368
8.6	Additional reading . . . . .	370
8.7	Exercises . . . . .	371
<b>9</b>	<b>Image stitching</b>	<b>375</b>
9.1	Motion models . . . . .	378
9.1.1	Planar perspective motion . . . . .	379
9.1.2	<i>Application: Whiteboard and document scanning</i> . . . . .	379
9.1.3	Rotational panoramas . . . . .	380
9.1.4	Gap closing . . . . .	382

## Contents

9.1.5	<i>Application: Video summarization and compression</i>	383
9.1.6	Cylindrical and spherical coordinates	385
9.2	Global alignment	387
9.2.1	Bundle adjustment	388
9.2.2	Parallax removal	391
9.2.3	Recognizing panoramas	392
9.2.4	Direct vs. feature-based alignment	393
9.3	Compositing	396
9.3.1	Choosing a compositing surface	396
9.3.2	Pixel selection and weighting (de-ghosting)	398
9.3.3	<i>Application: Photomontage</i>	403
9.3.4	Blending	403
9.4	Additional reading	406
9.5	Exercises	407
<b>10</b>	<b>Computational photography</b>	<b>409</b>
10.1	Photometric calibration	412
10.1.1	Radiometric response function	412
10.1.2	Noise level estimation	415
10.1.3	Vignetting	416
10.1.4	Optical blur (spatial response) estimation	416
10.2	High dynamic range imaging	419
10.2.1	Tone mapping	427
10.2.2	<i>Application: Flash photography</i>	434
10.3	Super-resolution and blur removal	436
10.3.1	Color image demosaicing	440
10.3.2	<i>Application: Colorization</i>	442
10.4	Image matting and compositing	443
10.4.1	Blue screen matting	445
10.4.2	Natural image matting	446
10.4.3	Optimization-based matting	450
10.4.4	Smoke, shadow, and flash matting	452
10.4.5	Video matting	454
10.5	Texture analysis and synthesis	455
10.5.1	<i>Application: Hole filling and inpainting</i>	457
10.5.2	<i>Application: Non-photorealistic rendering</i>	458
10.6	Additional reading	460
10.7	Exercises	461
<b>11</b>	<b>Stereo correspondence</b>	<b>467</b>
11.1	Epipolar geometry	471
11.1.1	Rectification	472
11.1.2	Plane sweep	474
11.2	Sparse correspondence	475
11.2.1	3D curves and profiles	476
11.3	Dense correspondence	477

11.3.1	Similarity measures . . . . .	479
11.4	Local methods . . . . .	480
11.4.1	Sub-pixel estimation and uncertainty . . . . .	482
11.4.2	<i>Application: Stereo-based head tracking</i> . . . . .	483
11.5	Global optimization . . . . .	484
11.5.1	Dynamic programming . . . . .	485
11.5.2	Segmentation-based techniques . . . . .	487
11.5.3	<i>Application: Z-keying and background replacement</i> . . . . .	489
11.6	Multi-view stereo . . . . .	489
11.6.1	Volumetric and 3D surface reconstruction . . . . .	492
11.6.2	Shape from silhouettes . . . . .	497
11.7	Additional reading . . . . .	499
11.8	Exercises . . . . .	500
<b>12</b>	<b>3D reconstruction</b>	<b>505</b>
12.1	Shape from X . . . . .	508
12.1.1	Shape from shading and photometric stereo . . . . .	508
12.1.2	Shape from texture . . . . .	510
12.1.3	Shape from focus . . . . .	511
12.2	Active rangefinding . . . . .	512
12.2.1	Range data merging . . . . .	515
12.2.2	<i>Application: Digital heritage</i> . . . . .	517
12.3	Surface representations . . . . .	518
12.3.1	Surface interpolation . . . . .	518
12.3.2	Surface simplification . . . . .	520
12.3.3	Geometry images . . . . .	520
12.4	Point-based representations . . . . .	521
12.5	Volumetric representations . . . . .	522
12.5.1	Implicit surfaces and level sets . . . . .	522
12.6	Model-based reconstruction . . . . .	523
12.6.1	Architecture . . . . .	524
12.6.2	Heads and faces . . . . .	526
12.6.3	<i>Application: Facial animation</i> . . . . .	528
12.6.4	Whole body modeling and tracking . . . . .	530
12.7	Recovering texture maps and albedos . . . . .	534
12.7.1	Estimating BRDFs . . . . .	536
12.7.2	<i>Application: 3D photography</i> . . . . .	537
12.8	Additional reading . . . . .	538
12.9	Exercises . . . . .	539
<b>13</b>	<b>Image-based rendering</b>	<b>543</b>
13.1	View interpolation . . . . .	545
13.1.1	View-dependent texture maps . . . . .	547
13.1.2	<i>Application: Photo Tourism</i> . . . . .	548
13.2	Layered depth images . . . . .	549
13.2.1	Impostors, sprites, and layers . . . . .	549

## Contents

13.3	Light fields and Lumigraphs . . . . .	551
13.3.1	Unstructured Lumigraph . . . . .	554
13.3.2	Surface light fields . . . . .	555
13.3.3	<i>Application</i> : Concentric mosaics . . . . .	556
13.4	Environment mattes . . . . .	556
13.4.1	Higher-dimensional light fields . . . . .	558
13.4.2	The modeling to rendering continuum . . . . .	559
13.5	Video-based rendering . . . . .	560
13.5.1	Video-based animation . . . . .	560
13.5.2	Video textures . . . . .	561
13.5.3	<i>Application</i> : Animating pictures . . . . .	564
13.5.4	3D Video . . . . .	564
13.5.5	<i>Application</i> : Video-based walkthroughs . . . . .	566
13.6	Additional reading . . . . .	569
13.7	Exercises . . . . .	570
<b>14</b>	<b>Recognition</b> . . . . .	<b>575</b>
14.1	Object detection . . . . .	578
14.1.1	Face detection . . . . .	578
14.1.2	Pedestrian detection . . . . .	585
14.2	Face recognition . . . . .	588
14.2.1	Eigenfaces . . . . .	589
14.2.2	Active appearance and 3D shape models . . . . .	596
14.2.3	<i>Application</i> : Personal photo collections . . . . .	601
14.3	Instance recognition . . . . .	602
14.3.1	Geometric alignment . . . . .	603
14.3.2	Large databases . . . . .	604
14.3.3	<i>Application</i> : Location recognition . . . . .	609
14.4	Category recognition . . . . .	611
14.4.1	Bag of words . . . . .	612
14.4.2	Part-based models . . . . .	615
14.4.3	Recognition with segmentation . . . . .	620
14.4.4	<i>Application</i> : Intelligent photo editing . . . . .	621
14.5	Context and scene understanding . . . . .	625
14.5.1	Learning and large image collections . . . . .	627
14.5.2	<i>Application</i> : Image search . . . . .	630
14.6	Recognition databases and test sets . . . . .	631
14.7	Additional reading . . . . .	631
14.8	Exercises . . . . .	637
<b>15</b>	<b>Conclusion</b> . . . . .	<b>641</b>
<b>A</b>	<b>Linear algebra and numerical techniques</b> . . . . .	<b>645</b>
A.1	Matrix decompositions . . . . .	646
A.1.1	Singular value decomposition . . . . .	646
A.1.2	Eigenvalue decomposition . . . . .	647

## Contents

A.1.3	QR factorization . . . . .	649
A.1.4	Cholesky factorization . . . . .	650
A.2	Linear least squares . . . . .	651
A.2.1	Total least squares . . . . .	653
A.3	Non-linear least squares . . . . .	654
A.4	Direct sparse matrix techniques . . . . .	655
A.4.1	Variable reordering . . . . .	656
A.5	Iterative techniques . . . . .	656
A.5.1	Conjugate gradient . . . . .	657
A.5.2	Preconditioning . . . . .	659
A.5.3	Multigrid . . . . .	660
<b>B</b>	<b>Bayesian modeling and inference</b>	<b>661</b>
B.1	Estimation theory . . . . .	662
B.1.1	Likelihood for multivariate Gaussian noise . . . . .	663
B.2	Maximum likelihood estimation and least squares . . . . .	665
B.3	Robust statistics . . . . .	666
B.4	Prior models and Bayesian inference . . . . .	667
B.5	Markov random fields . . . . .	668
B.5.1	Gradient descent and simulated annealing . . . . .	670
B.5.2	Dynamic programming . . . . .	670
B.5.3	Belief propagation . . . . .	672
B.5.4	Graph cuts . . . . .	674
B.5.5	Linear programming . . . . .	676
B.6	Uncertainty estimation (error analysis) . . . . .	678
<b>C</b>	<b>Supplementary material</b>	<b>679</b>
C.1	Data sets . . . . .	680
C.2	Software . . . . .	682
C.3	Slides and lectures . . . . .	689
C.4	Bibliography . . . . .	690
	<b>References</b>	<b>691</b>
	<b>Index</b>	<b>793</b>