

Index

symbols

- 3D image acquisition device 82–95, 292, 313, 315, 321
 - sheet of light sensor 84–86
 - stereo sensor 82–84
 - structured light sensor 86–91
- 3D object recognition 292–323
 - 3D data 293, 313–323
 - 3D object 292, 302–323
 - deformable matching 292–302
 - – 3D pose 297–299
 - – calibrated 293, 297–299
 - – circular structure 295–296
 - – clustering 295
 - – deformable object 300–302
 - – hierarchical search 297
 - – linear structure 295–296
 - – model generation 295
 - – model parts 295
 - – pose refinement 297
 - – principle 293–294
 - – similarity measure 295–296
 - – uncalibrated 293, 297
 - deformable object 292, 300–302
 - deformation model 300–301
 - depth data 313–323
 - image data 292–312
 - planar object 292–299
 - – calibrated 293, 297–299
 - – uncalibrated 293, 297
 - shape-based 3D matching 292, 302–312
 - – 2D matching pose 304–305
 - – 2D model generation 308–310
 - – 3D pose 304–305
 - – accuracy 305–306, 311–312
 - – applications 312
 - – CAD model 308–310
 - – degrees of freedom 304–305
 - – examples 312
 - – hierarchical model 307–308
 - – hierarchical search 307–308
 - – image pyramid 307, 309, 311
 - – minimum face angle 310
 - – model image 309–310
 - – multi-channel edge tensor 310
 - – perspective correction 310–311
 - – perspective distortions 305–306, 310–311
 - – pose range 306
 - – pose refinement 311–312
 - – principle 303–306
 - – robustness 305–307, 309–311
 - – run time 305–308
 - – spherical coordinates 306
 - – spherical projection 311
 - – view 305, 307–308
 - – view sphere 303–306
 - – view-based approach 303–306
 - – virtual camera 303–304, 307–308
 - surface-based 3D matching 293, 313–323, 443–459
 - – accumulator array 318–319
 - – accuracy 319–321
 - – corresponding points 319–321
 - – deformable object 321
 - – global model description 314–316
 - – hash table 315–316, 318, 319, 323
 - – Hough transform 318–319
 - – iterative closest point 319–321
 - – local parameters 316–318
 - – multimodal data 321–323
 - – non-maximum suppression 319
 - – normal vector 315–317
 - – planar object 323
 - – point pair 314–316
 - – point pair feature 314–316, 318, 322–323
 - – point sampling 315
 - – pose refinement 319–321, 323
 - – reference point 316–319, 322

- – robustness 322
- – score 319
- – search scene 314, 316, 318
- – voting 318–319, 323
- 3D reconstruction 292, 313, 315
 - sheet of light 33, 35, 84–86, 254–257
 - – calibration 256–257
 - – extraction of laser line 255–256
 - stereo 33, 82–84, 241–254, 425–432
 - structured light 33, 35, 86–91, 257–262
 - – binary code patterns 88
 - – camera calibration 258–261
 - – fringe projection 90–91
 - – Gray code decoding 257–258
 - – Gray code patterns 88–89, 91
 - – phase decoding 258
 - – phase shift 90–91
 - – projector calibration 258–261
 - – radiometric calibration 261–262
 - – stripe decoding 257–258
- a**
- a posteriori probability 343
- a priori probability 343, 346
- aberrations *see* lens aberrations
- absolute phase 91
- absolute sensitivity threshold 54
- absolute sum of normalized dot products 289
- accumulator array 278–280, 318
- accuracy 197–198
 - camera parameters 238–241
 - contour moments 159
 - edges 105, 199–203
 - gray value features 105
 - gray value moments 155–157, 159
 - hardware requirements 203
 - region moments 155–157
 - subpixel-precise threshold 105
- achromatic lens 39
- active pixel sensor 46
- ADC 42, 47, 58
- affine transformation 126–127, 152, 263, 281, 288, 408–413, 432–438
- Airy disk 27
- algebraic distance 210
- algebraic error 210
- aliasing 43, 44, 47, 123, 132, 268
- alignment 126, 141, 142
- amplifier noise 53
- analog-to-digital converter *see* camera, ADC
- Ando filter 190
- anisometry 151, 155, 158, 340, 377–383
- anti-bloom drain 45
- anti-extensive operation
 - erosion 164, 176
 - Minkowski subtraction 164, 176
 - opening 169, 177
- antisymmetric matrix 333
- aperture stop 23, 27–32, 36, 37, 39, 106
- apochromatic lens 39
- APS *see* camera, active pixel sensor
- area 149–150, 155, 156, 158, 377–383, 400–407, 414–421
- area of interest 47, 74, 75
- area sensor 43–47, 216
- articulated robot 323–324
- aspherical lens 36
- astigmatism 37, 201
- asynchronous reset 46, 48, 80
- b**
- back light 13
- back porch 57
- Bayes decision rule 343, 344
- Bayes theorem 343
- bilateral telecentric lens 30–32, 216, 222–224
- binary image 99, 146, 149, 160, 162, 166, 172
- binocular stereo reconstruction 33, 82–84, 241–254, 425–432
- black body 5–7
- blooming 45
- boundary 147, 154, 166–167
- bounding box 153, 158, 341, 377–388, 400–407
- bright-field illumination 13
- c**
- CAD model 298, 303, 304, 308–310, 312, 314, 315
- calibration
 - geometric 201, 203, 215–242, 258–261, 408–413
 - – accuracy of interior orientation 238–241
 - – binocular stereo calibration 243, 259–260, 425–432
 - – calibration target 230–231, 259
 - – camera constant *see* calibration, geometric, principal distance
 - – camera coordinate system 217–218, 226–227, 242
 - – camera motion vector 225–226
 - – distortion coefficient (division model) 219, 222, 227, 238–242, 245
 - – distortion coefficients (polynomial model) 219–222, 242
 - – exterior orientation 203, 232–235, 256, 425–432

- - focal length *see* calibration, geometric, principal distance
- - image coordinate system 221, 227–228
- - image plane coordinate system 219, 227
- - image plane distance 224–225, 242
- - interior orientation 83, 85, 86, 203, 232–235, 242, 256, 425–432
- - magnification 219, 222
- - pixel size 221, 227–228, 242
- - principal distance 18, 24, 216–217, 219, 222, 227, 238–242
- - principal point 221, 227–228, 238–242
- - projection center 18, 24, 83, 216, 242, 245, 248, 258
- - relative orientation 83, 86, 242, 260
- - world coordinate system 217–218, 226–227
- hand-eye *see* hand-eye calibration
- radiometric 105–110, 201, 261–262
 - - calibration target 105
 - - chart-based 105–106
 - - chartless 106–110
 - - defining equation for chartless calibration 107
 - - discretization of inverse response function 107–108
 - - gamma response function 105, 109
 - - inverse response function 107
 - - normalization of inverse response function 108
 - - polynomial inverse response function 109
 - - response function 105, 106, 109
 - - smoothness constraint 108–109
- camera 97–98
 - absolute sensitivity threshold 54
 - active pixel sensor 46
 - ADC 42, 47, 58
 - analog-to-digital converter *see* camera, ADC
 - area scan 43–47
 - asynchronous reset 46, 48, 80
 - calibration
 - - image rectification 238
 - - world coordinates from single image 202–203, 235–238, 256, 298
 - - world coordinates from stereo reconstruction 241–254
 - CCD 41–46
 - - anti-bloom drain 45
 - - blooming 45
 - - frame transfer sensor 43–44
 - - full frame sensor 43
 - - interlaced scan 46, 56
 - - interline transfer sensor 44–46
 - - lateral overflow drain 45
 - - line sensor 41–43
 - - progressive scan 46, 58
 - - vertical overflow drain 45
 - CMOS 46–48
 - - area of interest 47
 - - global shutter 48, 82
 - - line sensor 47
 - - rolling shutter 48
 - color 49–50
 - - single-chip 49–50
 - - three-chip 50
 - color filter array 49
 - - Bayer 49
 - - demosaicking 49
 - configuration 61, 63–66, 69
 - - GenICam 62, 63, 65, 69, 72–77, 79
 - - GenICam CLProtocol 62, 73
 - - GenICam GenApi 63, 65, 69, 72–77, 79
 - - GenICam GenCP 63, 69, 72–77
 - - GenICam PFNC *see* camera, configuration, GenICam pixel format naming convention
 - - GenICam pixel format naming convention 71–77
 - - GenICam SFNC *see* camera, configuration, GenICam standard features naming convention
 - - GenICam standard features naming convention 63, 65, 69, 71–77
 - IIDC 66
 - control *see* camera, configuration
 - dark signal nonuniformity 54
 - digital pixel sensor 47
 - dynamic range 54
 - exposure time 26, 42, 45, 106
 - fill factor 43, 44, 47, 48, 157, 200, 203
 - gamma response function 105, 109
 - gray value response 105, 261–262
 - - linear 105, 201, 203, 261
 - - nonlinear 105, 201, 261
 - inverse response function 107
 - line scan 41–43, 47, 216, 225–229, 238
 - - encoder 42
 - noise
 - - amplifier noise 53
 - - dark current noise 53
 - - dark noise 53
 - - noise floor 53
 - - overall system gain 53
 - - pattern noise 54
 - - photon noise 52

- quantization noise 53
- reset noise 52
- signal-to-noise ratio 53, 90, 92, 94
- spatial noise 54
- temporal noise 53
- performance 52–55
- perspective 216–222, 236–237
- photoresponse nonuniformity 54
- pinhole 18–19, 24–25, 216
- quantum efficiency 52
- response function 105, 106, 109
- saturation capacity 54
- sensor size 50–51
- spectral response 48, 50
- telecentric 216–222, 236, 408–413
- time-of-flight 91–95
 - continuous-wave-modulated 92–93
 - distance computation 93, 94
 - distance range 92, 93
 - phase demodulation 92
 - pulse-modulated 93–95
 - random errors 93–95
 - resolution 93, 95
 - scene intensity 92
 - systematic errors 93–95
 - time-of-flight computation 94
- trigger 42, 45, 80–81
- Camera Link 61–62
- Camera Link HS 62–63
- Canny filter 187, 192, 198, 388–392, 414–421
 - edge accuracy 199, 200
 - edge precision 198
- cardinal elements 21
- CCD *see* camera, CCD
- CCIR 56
- center of gravity 150–152, 155, 156, 158, 205, 206, 256, 377–383, 408–413
- central moments 150–152, 155, 158, 205
- CFA *see* camera, color filter array
- chamfer-3-4 distance 174
- characteristic function 99, 155, 176
- charge-coupled device *see* camera, CCD
- chessboard distance 173, 174
- chief ray *see* principal ray
- chromatic aberration 39, 201
- circle fitting 208–210, 377–383, 414–425
 - outlier suppression 209–210
 - robust 209–210
- circle of confusion 25, 36
- city-block distance 173, 174
- classification 342–370, 377–383, 438–443
 - a posteriori probability 343
 - a priori probability 343, 346
 - Bayes classifier 346–349
 - classifier types 345
 - curse of dimensionality 346, 359
 - decision theory 343–345
 - Bayes decision rule 343, 344
 - Bayes theorem 343
 - error rate 345
 - expectation maximization algorithm 348
 - features 339, 342, 377–383
 - Gaussian mixture model classifier 347–349
 - $k\sigma$ probability 348–349
 - novelty detection 348–349
 - generalized linear classifier 358
 - hyper-parameter 345, 347
 - k nearest-neighbor classifier 347
 - novelty detection 347
 - linear classifier 350–352
 - neural network 351–358, 377–383, 438–443
 - convolutional neural network 365–369
 - cross-entropy error 354, 368
 - dataset augmentation 369
 - evidence procedure 357
 - hyperbolic tangent activation function 353
 - logistic activation function 353
 - multilayer perceptron 352–358, 365, 377–383, 438–443
 - multilayer perceptron training 354–358
 - novelty detection 357–358, 369
 - rectified linear unit activation function 366
 - regularization 355–357, 368–369
 - sigmoid activation function 353–354
 - single-layer perceptron 351–352
 - softmax activation function 353, 366
 - threshold activation function 351, 352
 - universal approximator 353, 354, 365, 366
 - weight decay 355–357, 368
 - nonlinear classifier 352–369
 - novelty detection 345–346
 - Gaussian mixture model classifier 348–349
 - k nearest-neighbor classifier 347
 - polynomial classifier 358
 - rejection 345–346
 - support vector machine 358–364
 - Gaussian radial basis function kernel 362
 - homogeneous polynomial kernel 361
 - inhomogeneous polynomial kernel 362
 - kernel 361
 - margin 360
 - margin errors 362, 364

- – novelty detection 363–364
 - – ν -SVM 362
 - – one-versus-all 362–363
 - – one-versus-one 362–363
 - – separating hyperplane 359–361
 - – sigmoid kernel 362
 - – universal approximator 362
 - test set 345
 - training set 345, 354
 - validation set 345, 347, 356, 357
 - closing 170–172, 177–179, 400–407
 - clutter 273, 276, 280, 287–288
 - CMOS *see* camera, CMOS
 - CNN *see* convolutional neural network
 - CoaXPress 64–65
 - color filter 11, 50
 - color filter array *see* camera, color filter array
 - color temperature *see* correlated color temperature
 - coma 36–37, 201
 - compactness 154, 340, 377–383
 - complement 160
 - complementary metal-oxide-semiconductor *see* camera, CMOS
 - completeness checking 1
 - component labeling 146
 - composite video 58
 - connected components 144–146, 255, 338, 377–383, 392–407
 - connectivity 145–146, 160, 167, 173
 - contour 101
 - contour feature *see* features, contour
 - contour length 154
 - contour segmentation 211–214, 274, 383–388, 421–425
 - lines 211–213
 - lines and circles 213–214, 383–388, 421–425
 - lines and ellipses 213–214
 - contrast enhancement 102–104
 - contrast normalization 102–104
 - robust 103–104, 341, 367
 - convex hull 153, 158
 - convexity 153, 377–383
 - convolution 115–116, 122, 365
 - kernel 115
 - convolutional neural network 365–369
 - convolution 365–366
 - convolutional layer 366–367
 - filter stride 366
 - fine-tuning 367–368
 - learning rate 368
 - minibatch 368
 - momentum 368
 - novelty detection 369
 - pooling 366
 - receptive field 366
 - rectified linear unit 366
 - softmax activation function 366
 - stochastic gradient descent 368
 - training
 - – cross-entropy error 368
 - – dataset augmentation 369
 - – regularization 368–369
 - – weight decay 368
 - universal approximator 366
 - coordinates
 - homogeneous 126, 127
 - inhomogeneous 126, 127
 - polar 134
 - correlated color temperature 7, 8
 - correlation 122, 365, 371–377
 - *see also* normalized cross-correlation
 - cross-entropy error 354, 368
 - cumulative histogram 104, 154
 - curvature of field 37
 - cylindrical lens 84
- d**
- dark current noise 53
 - dark noise 53
 - dark signal nonuniformity 54
 - dark-field illumination 13
 - data structures
 - images 97–98
 - regions 98–100
 - subpixel-precise contours 101
 - dataset augmentation 369
 - datum deficiency 333
 - DCS *see* distributed control system
 - decision theory 343–345
 - a posteriori probability 343
 - a priori probability 343, 346
 - Bayes decision rule 343, 344
 - Bayes theorem 343
 - deep learning 365
 - deep neural network 365
 - deformable matching *see* 3D object recognition, deformable matching
 - demosaicking 49
 - depth of field 25–28, 30–36
 - depth-first search 145
 - Deriche filter 187–188, 192, 198
 - edge accuracy 199, 201
 - edge precision 198
 - derivative

- directional 182
 - first 180, 184
 - gradient 182
 - Laplacian 182
 - partial 182, 190, 191
 - second 180, 184
 - DFT *see* discrete Fourier transform
 - DHCP *see* Dynamic Host Configuration Protocol
 - diaphragm 22, 25, 36
 - difference 160, 400–407, 414–425
 - diffraction 27
 - diffuse bright-field back light illumination 16–17
 - diffuse bright-field front light illumination 13–14
 - diffuse illumination 12
 - digital input/output 3
 - digital light processing 87
 - digital micromirror device 87–88
 - diamond pixel array layout 88–89, 258
 - regular pixel array layout 88
 - digital pixel sensor 47
 - digital signal processor 2
 - dilation 161–163, 166–167, 176, 195, 388–392, 400–407, 421–425
 - dimensional inspection 1
 - direct memory access 58, 80
 - directed bright-field front light illumination 14–15
 - directed dark-field front light illumination 15
 - directed illumination 12
 - discrete Fourier transform 123–125
 - *see also* Fourier transform
 - disparity 249–250
 - dispersion 19
 - distance
 - chamfer-3-4 174
 - chessboard 173, 174
 - city-block 173, 174
 - Euclidean 173, 174, 414–421
 - distance transform 173–175, 275, 276, 414–421
 - distortion 37–38, 201, 219–222, 227, 303
 - barrel 37–38, 219–221, 227
 - division model 219, 222, 261
 - pincushion 37–38, 219–221, 227
 - polynomial model 219–222, 261
 - distributed control system 3
 - DLP *see* digital light processing
 - DMA *see* direct memory access
 - DMD *see* digital micromirror device
 - DSNU *see* dark signal nonuniformity
 - DSP *see* digital signal processor
 - dual number 330
 - dual part 330
 - dual unit 330
 - Plücker coordinates 330
 - real part 330
 - dual quaternion 327, 330–331
 - advantages 331
 - ambiguity 331
 - conjugation 330
 - dual part 330
 - inversion 330
 - line transformation 331
 - multiplication 330, 331
 - overparameterization 331
 - Plücker coordinates 330
 - pure 330
 - real part 330
 - scalar part 331, 336
 - screw 330–331
 - unit 330–331, 333
 - vector part 332
 - dual vector 330
 - duality
 - dilation–erosion 166, 177
 - hit-or-miss transform 168
 - opening–closing 170, 177
 - Dynamic Host Configuration Protocol 70
 - dynamic range 54
 - dynamic thresholding 138–141, 179, 257, 338, 377–383, 400–407
- e**
- edge
 - amplitude 144, 182, 191, 310
 - definition
 - – 1D 180–181
 - – 2D 181–183
 - gradient magnitude 144, 182, 191
 - gradient vector 182
 - Laplacian 182, 195–196
 - non-maximum suppression 180, 188, 192–193
 - polarity 181
 - edge extraction 180–203, 274, 421–425
 - 1D 183–189, 408–413
 - – Canny filter 187
 - – Deriche filter 187–188
 - – derivative 180, 184
 - – gray value profile 185–186, 408–413
 - – non-maximum suppression 188
 - – subpixel-accurate 189
 - 2D 144, 189–196, 388–392, 414–432, 438–443

- – Ando filter 190
- – Canny filter 192, 198
- – Deriche filter 192, 198
- – Frei filter 190
- – gradient 182
- – hysteresis thresholding 194
- – Lanser filter 192, 198
- – Laplacian 182, 195–196
- – non-maximum suppression 192–193
- – Prewitt filter 190
- – Sobel filter 190, 342
- – subpixel-accurate 194–196
- edge filter 144, 186–188
 - Ando 190
 - Canny 187, 192, 198, 388–392, 414–421
 - – edge accuracy 199, 200
 - – edge precision 198
 - Deriche 187–188, 192, 198
 - – edge accuracy 199, 201
 - – edge precision 198
 - Frei 190
 - Lanser 192, 198
 - – edge accuracy 199
 - – edge precision 198
 - optimal 187–188, 191–192
 - Prewitt 190
 - Sobel 190, 342
- edge-spread function 39–40
- EIA-170 56
- electromagnetic radiation 5–7
 - black body 5–7
 - infrared 5, 48, 92, 93
 - spectrum 5
 - ultraviolet 5, 48
 - visible 5
- ellipse fitting 210–211
 - algebraic error 210
 - geometric error 210
 - outlier suppression 210–211
 - robust 210–211
- ellipse parameters 150–153, 155, 158, 159, 205, 206, 210
- enclosing circle 153, 158
- enclosing rectangle 153, 158, 341, 377–388, 400–407
- encoder 42
- entocentric lens 28, 32, 216, 222, 224–225
- entrance pupil 23, 24, 29, 83, 216, 259
- epipolar image rectification 247–249, 425–432
- epipolar line 244
- epipolar plane 244
- epipolar standard geometry 245–247, 425–432
- epipole 244
- erosion 164–167, 176–177, 400–407, 421–425
- Ethernet 69–72
- Euclidean distance 173, 174, 414–421
- evidence procedure 357
- exit pupil 23, 24, 29, 30, 224, 258
- exposure time 26, 42, 45, 106
- extensible markup language *see* XML
- extensive operation
 - closing 171, 177
 - dilation 162, 176
 - Minkowski addition 161, 176
- exterior orientation 203, 217–218, 226–227, 232–235, 256, 260, 325, 408–413, 425–432
 - world coordinate system 217–218, 226–227
- f**
- f*-number 26, 30, 32, 36, 37, 39, 106
- facet model 194
- fast Fourier transform 124, 371–377
 - *see also* Fourier transform
- feature extraction 149–159, 392–400
- features
 - contour 149, 158–159, 383–388, 392–400
 - – area 158
 - – center of gravity 158
 - – central moments 158
 - – contour length 158, 383–388
 - – ellipse parameters 159
 - – major axis 159
 - – minor axis 159
 - – moments 158
 - – normalized moments 158
 - – orientation 159
 - – smallest enclosing circle 158
 - – smallest enclosing rectangle 158, 383–388
 - gray value 149, 154–158, 438–443
 - – α -quantile 155
 - – anisometry 155, 158
 - – area 155, 156, 158
 - – center of gravity 155, 156, 256
 - – central moments 155
 - – ellipse parameters 155, 158
 - – major axis 155, 158
 - – maximum 102, 154
 - – mean 154, 256
 - – median 155
 - – minimum 102, 154
 - – minor axis 155, 158
 - – moments 155–158
 - – normalized moments 155
 - – orientation 155
 - – standard deviation 154

- variance 154
- region 149–154, 377–383, 392–407, 414–421, 443–450
- anisometry 151, 340, 377–383
- area 149–150, 156, 377–383, 400–407, 414–421
- center of gravity 150–152, 156, 377–383
- central moments 150–152
- compactness 154, 340, 377–383
- contour length 154
- convexity 153, 377–383
- ellipse parameters 150–153
- major axis 150–152
- minor axis 150–152
- moments 150–152, 377–383
- normalized moments 150
- orientation 150–153
- smallest enclosing circle 153
- smallest enclosing rectangle 153, 341, 377–383, 400–407
- FFT *see* fast Fourier transform
- field angle 24
- field-programmable gate array 2
- fieldbus 3
- fill factor 43, 44, 47, 48, 157, 200, 203
- filter
 - anisotropic 116, 192
 - border treatment 113
 - convolution 115–116, 122, 365
 - kernel 115
 - definition 115
 - edge 186–188
 - Ando 190
 - Canny 187, 192, 198, 388–392, 414–421
 - Deriche 187–188, 192, 198
 - Frei 190
 - Lanser 192, 198
 - optimal 187–188, 191–192
 - Prewitt 190
 - Sobel 190, 342
 - Gaussian 117–119, 132, 138–140, 187, 192, 269
 - frequency response 118, 122
 - isotropic 117, 118, 192
 - linear 115–116, 184
 - mask 115
 - maximum *see* morphology, gray value, dilation
 - mean 112–114, 119, 132, 139, 140, 185, 268, 377–383, 400–407
 - frequency response 116, 122, 269
 - median 119–120, 139, 140, 400–407
 - minimum *see* morphology, gray value, erosion
 - nonlinear 119–120, 177
 - optical
 - anti-aliasing 49
 - color 11, 50
 - infrared cut 11, 50
 - infrared pass 11, 48
 - polarizing 11
 - rank 120, 177
 - recursive 114, 116, 118, 177
 - runtime complexity 114
 - separable 114, 115, 118
 - smoothing 110–120
 - optimal 117–118, 187, 191
 - spatial averaging 112–114
 - temporal averaging 111–112, 142
- FireWire *see* IEEE 1394
- fitting
 - circles 208–210, 377–383, 414–425
 - outlier suppression 209–210
 - robust 209–210
 - ellipses 210–211
 - algebraic error 210
 - geometric error 210
 - outlier suppression 210–211
 - robust 210–211
 - lines 204–208, 383–388
 - outlier suppression 205–208
 - robust 205–208
- fluorescent lamp 8
- focal length 20
 - *see also* principal distance
- focal point 20
- focusing plane 25, 33
- Fourier transform 116, 120–125, 371–377
 - 1D 121
 - inverse 121
 - 2D 122, 371–377
 - inverse 122, 371–377
 - continuous 120–122
 - convolution 122
 - discrete 123–125
 - inverse 124
 - fast 124, 371–377
 - frequency domain 121
 - Nyquist frequency 123
 - real-valued 124, 371–377
 - spatial domain 121
 - texture removal 124–125
- FPGA *see* field-programmable gate array
- frame grabber 55
 - analog 58–60

- – line jitter 59–60, 199
 - – pixel clock 58, 60
 - frame transfer sensor 43–44
 - Frei filter 190
 - frequency domain 121
 - fringe projection 90–91, 258
 - front light 13
 - front porch 57
 - full frame sensor 43
 - fuzzy membership 155–158
 - fuzzy set 155–158
- g**
- gamma response function 105, 109
 - gauge freedom 333
 - Gaussian filter 117–119, 132, 138–140, 187, 192, 269
 - frequency response 118, 122
 - Gaussian mixture model 347–349
 - $k\sigma$ probability 348–349
 - novelty detection 348–349
 - Gaussian optics 19–31
 - GenApi *see* GenICam, GenApi
 - GenCP *see* GenICam, GenCP
 - generalized Hough transform 277–280, 318
 - accumulator array 278–280
 - R-table 280
 - GenICam 62, 63, 65, 69, 72–77, 79
 - CLProtocol 62, 73
 - GenApi 63, 65, 69, 72–77, 79
 - GenCP 63, 69, 72–77
 - GenTL 65, 77–79
 - – GenTL consumer 78
 - – GenTL producer 77
 - – SFNC *see* GenICam, GenTL, standard features naming convention
 - – standard features naming convention 77–79
 - PFNC *see* GenICam, pixel format naming convention
 - pixel format naming convention 71–77
 - SFNC *see* GenICam, standard features naming convention
 - standard features naming convention 63, 65, 69, 71–77
 - transport layer 73, 77–79
 - GenTL *see* GenICam, GenTL
 - geometric camera calibration 201, 203, 215–242, 258–261, 408–413
 - binocular stereo calibration 243, 259–260, 425–432
 - calibration target 230–231, 259
 - exterior orientation 203, 217–218, 226–227, 232–235, 256, 260, 408–413, 425–432
 - – world coordinate system 217–218, 226–227
 - interior orientation 83, 85, 86, 203, 216–222, 232–235, 242, 256, 260, 298, 303, 408–413, 425–432
 - – accuracy 238–241
 - – camera constant *see* geometric camera calibration, interior orientation, principal distance
 - – camera coordinate system 217–218, 226–227, 242
 - – camera motion vector 225–226
 - – distortion coefficient (division model) 219, 222, 227, 238–242, 245
 - – distortion coefficients (polynomial model) 219–222, 242
 - – focal length *see* geometric camera calibration, interior orientation, principal distance
 - – image coordinate system 221, 227–228
 - – image plane coordinate system 219, 227
 - – image plane distance 224–225, 242
 - – magnification 219, 222
 - – pixel size 221, 227–228, 242
 - – principal distance 18, 24, 216–217, 219, 222, 227, 238–242
 - – principal point 221, 227–228, 238–242
 - – projection center 18, 24, 83, 216, 242, 245, 248, 258
 - – tilt angle 222–225, 242
 - – tilt axis angle 222–225, 242
 - relative orientation 83, 86, 242, 260
 - – base 83, 242
 - – base line 245
 - geometric error 210
 - geometric hashing 281–283
 - geometric matching 281–291
 - GEV *see* GigE Vision
 - Gigabit Ethernet *see* GigE Vision
 - GigE Vision 70–72
 - control channel 71
 - GigE Vision Control Protocol 71
 - GigE Vision Streaming Protocol 71
 - GVCP *see* GigE Vision, GigE Vision Control Protocol
 - GVSP *see* GigE Vision, GigE Vision Streaming Protocol
 - message channel 71
 - stream channel 71
 - global shutter 48, 82
 - GMM *see* Gaussian mixture model
 - gradient 182
 - amplitude 144, 182, 191

- angle 182, 279
- direction 182, 277, 279
- length 182
- magnitude 144, 182, 191
- morphological 179
- Gray code 88–89, 91, 257–258
- gray value 98
 - 1D histogram 103–104, 136–138, 154
 - – cumulative 104, 154
 - – maximum 136–138
 - – minimum 136–138
 - – peak 136–138
 - 2D histogram 107–108
 - α -quantile 155
 - camera response 105, 261–262
 - – linear 105, 201, 203, 261
 - – nonlinear 105, 201, 261
 - feature *see* features, gray value
 - maximum 102, 154
 - mean 154, 256
 - median 155
 - minimum 102, 154
 - normalization 102–104
 - – robust 103–104, 341
 - profile 185
 - robust normalization 341, 367
 - scaling 102
 - standard deviation 154
 - transformation 102–104, 154, 157
 - variance 154
- GVCP *see* GigE Vision, GigE Vision Control Protocol
- GVSP *see* GigE Vision, GigE Vision Streaming Protocol

h

- Hamming distance 89
- hand-eye calibration 323–337, 451–459
 - algebraic error 335
 - articulated robot 331–335, 451–459
 - – linear 327, 331–335
 - – nonlinear 327, 334–335
 - base coordinate system 324
 - calibration object 325–327
 - camera coordinate system 324
 - coordinate systems 324
 - input poses 334
 - moving camera 324–326
 - poses 326
 - practical advice 333, 336
 - requirements 332
 - robot pose 325
 - SCARA robot 335–337

- – ambiguity 336–337
- – linear 336
- – nonlinear 337
- screw congruence theorem 332, 334
- stationary camera 324–326
- tool coordinate system 324
- transformations 326
- unity constraint 333, 336
- world coordinate system 324
- Hausdorff distance 276–277
- Hessian normal form 204
- hinge line 34
- histogram
 - 1D 103–104, 136–138, 154
 - – cumulative 104, 154
 - – maximum 136–138
 - – minimum 136–138
 - – peak 136–138
 - 2D 107–108
- hit-or-miss opening 169
- hit-or-miss transform 167–168, 172
- homogeneous coordinates 126, 127
- horizontal blanking interval 56
- horizontal synchronization pulse 57
- Huber weight function 207
- hypothesize-and-test paradigm 281
- hysteresis Thresholding 194

i

- ICP *see* iterative closest point
- IDE *see* integrated development environment
- idempotent operation
 - closing 170, 177
 - opening 169, 177
- identification 1
- IEEE 1394 65–66
 - asynchronous data transfer 66
 - IIDC 65–66
 - isochronous data transfer 66
- IIDC 65–66
- illumination 5–18
 - back light 13
 - bright-field 13
 - dark-field 13
 - diffuse 12
 - diffuse bright-field back light illumination 16–17
 - diffuse bright-field front light illumination 13–14
 - directed 12
 - directed bright-field front light illumination 14–15
 - directed dark-field front light illumination 15

- front light 13
 - light sources 7–8
 - – fluorescent lamp 8
 - – incandescent lamp 7
 - – LED *see* illumination, light sources, light-emitting diode
 - – light-emitting diode 8
 - – xenon lamp 7–8
 - telecentric 12
 - telecentric bright-field back light illumination 17–18
 - image 97–98
 - binary 99, 146, 149, 160, 162, 166, 172
 - bit depth 98
 - complement 177
 - domain *see* region of interest
 - enhancement 101–120
 - function 98–99
 - gray value 98
 - gray value normalization 102–104
 - – robust 103–104, 341, 367
 - gray value scaling 102
 - gray value transformation 102–104
 - label 99, 146
 - multichannel 98
 - noise *see* noise
 - pyramid 268–271, 290, 293–294, 297, 300, 307–311
 - rectification 129, 133, 238, 247–249, 292, 293, 300, 303, 338, 425–432
 - RGB 98
 - segmentation *see* segmentation
 - single-channel 98
 - smoothing 110–120
 - spatial averaging 112–114
 - temporal averaging 111–112, 142
 - transformation 128–134, 141, 388–392, 432–438
 - image acquisition modes 79–82
 - asynchronous acquisition 80
 - continuous acquisition 82
 - queued acquisition 81
 - synchronous acquisition 79–80
 - triggered acquisition 80–81
 - image distance 21, 25
 - image plane 18, 21, 25, 32, 33, 216, 222, 242, 245, 247, 249
 - tilted 33–35, 82, 84, 86, 222–225
 - image-side telecentric lens 31–32, 216, 222–224
 - incandescent lamp 7
 - increasing operation
 - closing 171, 177
 - dilation 162, 176
 - erosion 165, 176
 - Minkowski addition 161, 176
 - Minkowski subtraction 164, 176
 - opening 169, 177
 - infrared cut filter 11, 50
 - infrared pass filter 11, 48
 - inhomogeneous coordinates 126, 127
 - integrated development environment 74
 - interior orientation 83, 85, 86, 203, 216–222, 225–229, 232–235, 242, 256, 260, 297, 303, 325, 408–413, 425–432
 - accuracy 238–241
 - camera constant *see* interior orientation, camera constant
 - camera coordinate system 217–218, 226–227, 242
 - camera motion vector 225–226
 - distortion coefficient (division model) 219, 222, 227, 238–242, 245
 - distortion coefficients (polynomial model) 219–222, 242
 - focal length *see* interior orientation, principal distance
 - image plane coordinate system 219, 221, 227–228
 - image plane distance 224–225, 242
 - magnification 219, 222
 - pixel size 221, 227–228, 242
 - principal distance 18, 24, 216–217, 219, 222, 227, 238–241
 - principal point 221, 227–228, 238–242
 - projection center 18, 24, 83, 216, 242, 245, 248, 258
 - tilt angle 222–225, 242
 - tilt axis angle 222–225, 242
 - interlaced scan 46, 56
 - interline transfer sensor 44–46
 - Internet Protocol 70
 - interpolation
 - bicubic 130–132
 - bilinear 129–130, 147, 185, 260
 - nearest-neighbor 128–129, 185
 - intersection 160, 400–407, 414–421
 - invariant moments 152
 - IP *see* Internet Protocol
 - iterative closest point 319–321
 - iteratively reweighted least-squares 207
- j**
- junction 101
- k**
- kernel *see* convolution, kernel *and* support

vector machine, kernel

I

- label image 99, 146
- labeling 146
- Lanser filter 192, 198
 - edge accuracy 199
 - edge precision 198
- Laplacian 182, 195–196
- laser projector 84
 - cylindrical lens 84
 - Powell lens 84
 - raster lens 84
- laser triangulation 84–86, 254–257
 - calibration 256–257
 - extraction of laser line 255–256
- lateral overflow drain 45
- law of refraction 19
- LCD *see* liquid-crystal display
- LCOS *see* liquid crystal on silicon
- LED *see* light-emitting diode
- lens 19–31
 - achromatic 39
 - Airy disk 27
 - aperture stop 23, 27–32, 36, 37, 39, 106
 - apochromatic 39
 - aspherical 36
 - cardinal elements 21
 - chief ray *see* lens, principal ray
 - circle of confusion 25, 36
 - cylindrical 84
 - depth of field 25–28, 30–36
 - diaphragm 22, 25, 36
 - diffraction 27
 - entocentric 28, 32, 216, 222, 224–225
 - entrance pupil 23, 24, 29, 83, 216, 259
 - exit pupil 23, 24, 29, 30, 224, 258
 - f -number 26, 30, 32, 36, 37, 39, 106
 - field angle 24
 - focal length 20
 - focal point 20
 - focusing plane 25, 33
 - image distance 21, 25
 - image plane 18, 21, 25, 32, 33, 216, 222
 - – tilted 33–35, 82, 84, 86, 222–225
 - magnification 21, 27, 32, 33, 82, 86, 219
 - nodal point 21
 - numerical aperture 30
 - object distance 21, 25
 - optical axis 21, 222
 - perspective 32, 216
 - Powell lens 84
 - principal plane 20
 - principal ray 23, 24
 - pupil magnification factor 23, 225
 - raster lens 84
 - sagittal focal surface 37
 - sagittal image 37
 - Scheimpflug lens 36, 82, 84, 86, 258
 - Scheimpflug optics 36
 - Scheimpflug principle 32–36
 - surface vertex 21
 - system of lenses 22
 - tangential focal surface 37
 - tangential image 37
 - telecentric 28–32, 216
 - thick 20–22
 - tilt lens 32–36, 82, 84, 86, 222–225, 258
 - – hinge line 34
 - – Scheimpflug line 33–34
 - vignetting 40–41, 106
 - lens aberrations 20, 36–40
 - astigmatism 37, 201
 - chromatic aberration 39, 201
 - coma 36–37, 201
 - curvature of field 37
 - distortion 37–38, 201, 219–222, 227, 303
 - – barrel 37–38, 219–221, 227
 - – pincushion 37–38, 219–221, 227
 - spherical aberration 36
 - light 5, 48
 - absorption 9
 - polarized 9
 - reflection 8
 - refraction 9, 19
 - spectrum 5
 - – black body 5–7
 - light sources 7–8
 - fluorescent lamp 8
 - incandescent lamp 7
 - LED *see* light sources, light-emitting diode
 - light-emitting diode 8
 - xenon lamp 7–8
 - light-emitting diode 8
 - line
 - Hessian normal form 204
 - Plücker coordinates 330
 - line fitting 204–208, 383–388
 - outlier suppression 205–208
 - robust 205–208
 - line jitter 59–60, 199
 - line scan camera 41–43, 47, 216, 225–229, 238
 - line sensor 41–43, 47, 216
 - Link-Local Address 70
 - liquid crystal on silicon 87
 - liquid-crystal display 87

LLA *see* Link-Local Address

local deformation 292

look-up table 102, 107

low-voltage differential signaling 61

LUT *see* look-up table

LVDS *see* low-voltage differential signaling

m

magnification 21, 32, 33, 82, 86, 219

major axis 150–152, 155, 158, 159, 205, 206

maximum filter *see* morphology, gray value, dilation

maximum likelihood estimator 348

mean filter 112–114, 119, 132, 139, 140, 185, 268, 377–383, 400–407

– frequency response 116, 122, 269

mean squared edge distance 274–276

median filter 119–120, 139, 140, 400–407

minimum filter *see* morphology, gray value, erosion

Minkowski addition 161–162, 166, 175–176

Minkowski subtraction 163–166, 176

minor axis 150–152, 155, 158, 159, 205

MLP *see* multilayer perceptron

moments 150–152, 155–158, 377–383

– invariant 152

morphology 159–179, 338, 400–407, 414–425

– anti-extensive operation

– – erosion 164, 176

– – Minkowski subtraction 164, 176

– – opening 169, 177

– duality

– – dilation–erosion 166, 177

– – hit-or-miss transform 168

– – opening–closing 170, 177

– extensive operation

– – closing 171, 177

– – dilation 162, 176

– – Minkowski addition 161, 176

– gray value

– – closing 177–179

– – complement 177

– – dilation 176, 388–392

– – erosion 176–177

– – gradient 179

– – Minkowski addition 175–176

– – Minkowski subtraction 176

– – opening 177–179

– – range 179

– idempotent operation

– – closing 170, 177

– – opening 169, 177

– increasing operation

– – closing 171, 177

– – dilation 162, 176

– – erosion 165, 176

– – Minkowski addition 161, 176

– – Minkowski subtraction 164, 176

– – opening 169, 177

– region 159–175, 400–407, 414–432

– – boundary 166–167

– – closing 170–172, 400–407

– – complement 160

– – difference 160, 400–407, 414–425

– – dilation 161–163, 195, 400–407, 421–425

– – distance transform 173–175, 275, 276, 414–421

– – erosion 164–167, 400–407, 421–425

– – hit-or-miss opening 169

– – hit-or-miss transform 167–168, 172

– – intersection 160, 400–407, 414–421

– – Minkowski addition 161–162, 166

– – Minkowski subtraction 163–166

– – opening 168–170, 400–407, 414–421

– – skeleton 172–173, 414–421

– – translation 160

– – transposition 160–161

– – union 159–160, 400–407

– structuring element 161, 167, 175, 176, 400–407

– translation-invariant operation

– – closing 170

– – opening 169

multi-channel edge tensor 310

multilayer perceptron 352–358, 365

– evidence procedure 357

– novelty detection 357–358

– training 354–358

– – cross-entropy error 354

– – regularization 355–357

– – weight decay 355–357

– universal approximator 353, 354, 365

n

neighborhood 145–146, 167, 173

neural network 351–358, 377–383, 438–443

– activation function

– – hyperbolic tangent 353

– – logistic 353

– – rectified linear unit 366

– – sigmoid 353–354

– – softmax 353, 366

– – threshold 351, 352

– convolutional neural network 365–369

– – convolution 365–366

– – convolutional layer 366–367

- – cross-entropy error 368
- – dataset augmentation 369
- – filter stride 366
- – fine-tuning 367–368
- – learning rate 368
- – minibatch 368
- – momentum 368
- – novelty detection 369
- – pooling 366
- – receptive field 366
- – regularization 368–369
- – stochastic gradient descent 368
- – universal approximator 366
- – weight decay 368
- multilayer perceptron 352–358, 365, 377–383, 438–443
 - – cross-entropy error 354
 - – evidence procedure 357
 - – novelty detection 357–358
 - – regularization 355–357
 - – training 354–358
 - – universal approximator 353, 354, 365
 - – weight decay 355–357
- single-layer perceptron 351–352
- nodal point 21
- noise 110–111
 - amplifier noise 53
 - dark current noise 53
 - dark noise 53
 - noise floor 53
 - pattern noise 54
 - photon noise 52
 - quantization noise 53
 - reset noise 52
 - signal-to-noise ratio 53, 90, 92, 94
 - spatial noise 54
 - speckle 86
 - suppression 111–120
 - temporal noise 53
 - variance 110–113, 118–119, 185, 198
- non-maximum suppression 180, 188, 192–193
- normal distribution 348
- normalized cross-correlation 251, 264–267, 432–438
- normalized moments 150, 155, 158, 205, 206
- novelty detection *see* classification, novelty detection
- NTSC 56
- numerical aperture 30
- Nyquist frequency 123
- o**
- object distance 21, 25
- object identification 1
- object recognition *see* 3D object recognition
- object-side telecentric lens 28–32, 216, 222, 224–225
- occlusion 83, 85–87, 251, 253, 255, 257, 273, 276, 280, 287–288
- OCR *see* optical character recognition
- opening 168–170, 177–179, 400–407, 414–421
- optical anti-aliasing filter 49
- optical axis 21, 222
- optical character recognition 104, 126, 127, 149, 150, 337–342, 377–383, 432–438
 - character segmentation 338–339, 377–383
 - – touching characters 338–339
 - classification *see* classification
 - features 339–342, 377–383
 - image rectification 129, 133, 338
- orientation 150–153, 155, 159
 - exterior 203, 217–218, 226–227, 232–235, 256, 260, 408–413, 425–432
 - – world coordinate system 217–218, 226–227
 - interior 83, 85, 86, 203, 216–222, 225–229, 232–235, 242, 256, 260, 297, 303, 408–413, 425–432
 - – accuracy 238–241
 - – camera constant *see* orientation, interior, principal distance
 - – camera coordinate system 217–218, 226–227, 242
 - – camera motion vector 225–226
 - – distortion coefficient (division model) 219, 222, 227, 238–242, 245
 - – distortion coefficients (polynomial model) 219–222, 242
 - – focal length *see* orientation, interior, principal distance
 - – image plane coordinate system 219, 221, 227–228
 - – image plane distance 224–225, 242
 - – magnification 219, 222
 - – pixel size 221, 227–228, 242
 - – principal distance 18, 24, 216–217, 219, 222, 227, 238–241
 - – principal point 221, 227–228, 238–242
 - – projection center 18, 24, 83, 216, 242, 245, 248, 258
 - – tilt angle 222–225, 242
 - – tilt axis angle 222–225, 242
 - relative 83, 86, 242, 260
 - – base 83, 242
 - – base line 245

outlier 204, 205
 outlier suppression 205–211
 – Huber weight function 207
 – iteratively reweighted least-squares 207
 – random sample consensus 208
 – RANSAC 208
 – Tukey weight function 207
 overall system gain 53

p

PAL 56
 parallax 82, 85
 paraxial approximation 20
 pattern noise 54
 perspective camera 216–222, 236–237, 310
 – projection center 83, 216, 242, 245, 248, 258, 311
 perspective lens 32, 216, 310
 perspective transformation 127–128, 133, 224, 292, 293, 338
 PFNC *see* GenICam, pixel format naming convention
 phase shift 90–91, 258
 phase unwrapping 91, 92
 photon noise 52
 photoresponse nonuniformity 54
 pinhole camera 18–19, 24–25, 216
 – projection center 18, 24
 pixel 97–98
 pixel clock 58, 60
 pixel vignetting 32
 PLC *see* programmable logic controller
 Plücker coordinates 329, 330
 – line representation 330
 polar coordinates 134
 polar transformation 133–134, 338, 377–383
 polarization 9
 polarizing filter 11
 polygonal approximation 211–213
 – Ramer algorithm 212–213
 pose 126, 217–218, 226–227, 262, 292, 293, 297–299, 304, 305, 313, 316, 318, 323–324, 326, 329, 408–413
 position detection 1
 Powell lens 84
 precision 197–198
 – edge angle 280
 – edges 198–199
 – hardware requirements 199
 – phase 90–91
 Precision Time Protocol 72
 Prewitt filter 190
 principal distance 18, 24, 216–217

principal plane 20
 principal point 221, 227–228, 238–242
 principal ray 23, 24
 print inspection 140–144
 PRNU *see* photoresponse nonuniformity
 programmable logic controller 2
 progressive scan 46, 58
 projection center 18, 24, 83, 216, 242, 245, 248, 258
 projective transformation 127–128, 133, 224, 263, 293, 296–298, 311, 338
 projector
 – laser 84
 – – cylindrical lens 84
 – – Powell lens 84
 – – raster lens 84
 – random texture 83–84
 – structured light 86
 – – digital light processing 87
 – – digital micromirror device 87–88
 – – liquid crystal on silicon display 87
 – – liquid-crystal 87
 PTP *see* Precision Time Protocol
 pupil magnification factor 23, 225
 pure dual quaternion 330
 pure quaternion 328

q

quadratic programming 361, 362, 364
 quantization noise 53
 quantum efficiency 52
 quaternion 327–330
 – advantages 328–329
 – ambiguity 328
 – basis elements 327
 – conjugation 327
 – exponential form 328
 – interpolation 329
 – inversion 328
 – multiplication 327, 328
 – norm 327
 – overparameterization 329
 – pure 328, 330
 – rotation 328, 329
 – scalar part 327
 – unit 327–330
 – vector part 327

r

radiometric camera calibration 105–110, 201, 261–262
 – calibration target 105
 – chart-based 105–106
 – chartless 106–110

- defining equation 107
 - gamma response function 105, 109
 - inverse response function 107
 - discretization 107–108
 - normalization 108
 - polynomial 109
 - smoothness constraint 108–109
 - response function 105, 106, 109
 - Ramer algorithm 212–213
 - rank filter 120, 177
 - raster lens 84
 - reflection 8
 - reflectivity 9
 - refraction 9, 19
 - refractive index 19
 - region 98–100
 - as binary image 99, 146, 149, 160, 162, 166, 172
 - boundary 154, 166–167
 - characteristic function 99, 155, 176
 - complement 160
 - connected components 144–146, 255, 338, 377–383, 392–407
 - convex hull 153
 - definition 98
 - difference 160, 400–407, 414–425
 - feature *see* features, region
 - intersection 160, 400–407, 414–421
 - run-length representation 99–100, 145, 149, 150, 160, 162, 172
 - translation 160
 - transposition 160–161
 - union 159–160, 400–407
 - region of interest 99, 126, 128, 163, 175, 195, 263
 - regularization 355–357, 368–369
 - relative orientation 83, 86, 242, 260
 - base 83, 242
 - base line 245
 - reset noise 52
 - RGB video 58
 - rigid 3D transformation 218, 326, 329–333
 - rigid transformation 217, 262, 273, 281, 291, 408–413
 - robot 323–337
 - articulated 323–324, 335
 - base 323, 326
 - controller 326
 - end effector 323
 - joints 323–324, 335
 - kinematics 323, 324
 - mechanical interface 323, 324
 - movement 326–327, 333
 - SCARA 335
 - tool 323, 324, 326
 - tool center point 324
 - ROI *see* region of interest
 - rolling shutter 48
 - rotation 127, 129, 152, 262, 273, 338, 400–407
 - R-table 280
 - run-length encoding 99–100, 145, 149, 150, 160, 162, 172
- S**
- sagittal focal surface 37
 - sagittal image 37
 - saturation capacity 54
 - scaling 127, 132, 152, 262, 273
 - SCARA robot 335
 - Scheimpflug lens 36, 82, 84, 86, 258
 - Scheimpflug line 33–34
 - Scheimpflug optics 36
 - Scheimpflug principle 32–36
 - screw 329–331, 336
 - angle 329–332
 - axis 329, 332, 336
 - Chasles’ theorem 329
 - direction 329–331
 - dual quaternion 330–331
 - moment 329–331
 - Plücker coordinates 329
 - rotation 329, 330
 - translation 329–332
 - screw theory 327, 329–330
 - segmentation 135–149, 392–400, 414–425
 - connected components 144–146, 255, 338, 377–383, 392–407
 - dynamic thresholding 138–141, 179, 257, 338, 377–383, 400–407
 - hysteresis thresholding 194
 - subpixel-precise thresholding 147–149, 195, 383–388, 392–400
 - thresholding 135–138, 255, 338, 392–400, 414–425
 - automatic threshold selection 136–138, 338
 - variation model 141–144, 388–392, 400–407
 - sensor 97–98
 - serial interface 3
 - SFNC *see* GenICam, standard features naming convention *and* GenICam, GenTL, standard features naming convention
 - shape inspection 1
 - shape-based 3D matching *see* 3D object recognition, shape-based 3D matching

- shape-based matching 287–292, 294, 295, 302–304, 310, 371–377, 408–413, 432–438
- sheet of light reconstruction 33, 35, 84–86, 254–257, 443–450
 - calibration 256–257
 - extraction of laser line 255–256
 - occlusion 85–86, 255
- shutter
 - electronic 45
 - global 48, 82
 - mechanical 43, 44
 - rolling 48
- signal-to-noise ratio 52, 53, 90, 92, 94, 187, 198, 199, 280
- similarity measure 263–267, 288–290
 - absolute sum of normalized dot products 289
 - normalized cross-correlation 251, 264–267, 432–438
 - sum of absolute gray value differences 250, 263–264, 266–267
 - sum of absolute normalized dot products 289, 307
 - sum of normalized dot products 288–289
 - sum of squared gray value differences 250, 263–264
 - sum of unnormalized dot products 288
- similarity transformation 262, 273, 281, 292, 296, 297, 305, 392–400
- singular value 333, 336
- singular value decomposition 333
- skeleton 172–173, 414–421
- skew 127
- slant 127
- smallest enclosing circle 153, 158
- smallest enclosing rectangle 153, 158, 341, 377–388, 400–407
- smart camera 2
- smoothing filter 110–120
 - Gaussian 117–119, 132, 138–140, 187, 192, 269
 - – frequency response 118, 122
 - mean 112–114, 119, 132, 139, 140, 185, 268, 377–383, 400–407
 - – frequency response 116, 122, 269
 - median 119–120, 139, 140, 400–407
 - optimal 117–118, 187, 191
 - spatial averaging 112–114
 - temporal averaging 111–112, 142
- SNR *see* signal-to-noise ratio
- Sobel filter 190, 342
- spacetime stereo 254
- spatial averaging 112–114
- spatial domain 121
- spatial noise 54
- speckle noise 86
- spectral response
 - Gaussian filter 118, 122
 - human visual system 48
 - mean filter 116, 122, 269
 - sensor 48, 50, 98
- speed of light 6, 92
- spherical aberration 36
- stereo geometry 82–83, 242–250
 - corresponding points 83–84, 244
 - disparity 249–250
 - epipolar line 244
 - epipolar plane 244
 - epipolar standard geometry 245–247, 425–432
 - epipole 244
 - image rectification 247–249, 425–432
 - parallax 82, 85
- stereo matching 250–254, 425–432
 - occlusion 83, 251, 253
 - robust 253–254
 - – disparity consistency check 253
 - – excluding weakly textured areas 253
 - similarity measure
 - – normalized cross-correlation 251
 - – sum of absolute gray value differences 250
 - – sum of squared gray value differences 250
 - spacetime stereo 254
 - subpixel-accurate 252
 - window size 84, 252–253
- stereo reconstruction 33, 82–84, 241–254, 314, 321, 425–432
- stochastic process 111, 112
 - ergodic 112
 - stationary 111
- structured light reconstruction 33, 35, 86–91, 257–262
 - binary code patterns 88
 - camera calibration 258–261
 - fringe projection 90–91
 - Gray code decoding 257–258
 - Gray code patterns 88–89, 91
 - occlusion 86–87, 257
 - phase decoding 258
 - phase shift 90–91
 - projector calibration 258–261
 - radiometric calibration 261–262
 - stripe decoding 257–258
- structuring element 161, 167, 175, 176, 400–407

- subpixel-precise contour 101
 - convex hull 158
 - features *see* features, contour
 - subpixel-precise thresholding 147–149, 195, 383–388, 392–400
 - sum of absolute gray value differences 250, 263–264, 266–267
 - sum of absolute normalized dot products 289, 307
 - sum of normalized dot products 288–289
 - sum of squared gray value differences 250, 263–264
 - sum of unnormalized dot products 288
 - support vector machine 358–364
 - kernel 361
 - – Gaussian radial basis function 362
 - – homogeneous polynomial 361
 - – inhomogeneous polynomial 362
 - – sigmoid 362
 - margin 360
 - margin errors 362, 364
 - novelty detection 363–364
 - *v*-SVM 362
 - one-versus-all 362–363
 - one-versus-one 362–363
 - separating hyperplane 359–361
 - universal approximator 362
 - surface inspection 1
 - surface vertex 21
 - surface-based 3D matching 293, 313–323, *see* 3D object recognition, surface-based 3D matching, 443–459
 - SVD 333
 - S-Video 58
 - SVM *see* support vector machine
- t**
- tangential focal surface 37
 - tangential image 37
 - TCP *see* Transmission Control Protocol
 - telecentric bright-field back light illumination 17–18
 - telecentric camera 216–222, 236, 408–413
 - telecentric illumination 12
 - telecentric lens 28–32, 216
 - bilateral 30–32, 216, 222–224
 - image-side 31–32, 216, 222–224
 - object-side 28–32, 216, 222, 224–225
 - template matching 141, 262–292, 338
 - clutter 273, 276, 280, 287–288
 - erosion 165
 - generalized Hough transform 277–280
 - – accumulator array 278–280
 - – R-table 280
 - geometric hashing 281–283
 - geometric matching 281–291
 - Hausdorff distance 276–277
 - hierarchical search 270–271, 290
 - hit-or-miss transform 167
 - hypothesize-and-test paradigm 281
 - image pyramid 268–271, 290, 307
 - linear illumination changes 265
 - matching geometric primitives 283–286
 - mean squared edge distance 274–276
 - nonlinear illumination changes 273, 280, 287–289
 - occlusion 273, 276, 280, 287–288
 - opening 169, 400–407
 - robust 273–292, 371–377, 388–392, 400–413, 432–438
 - rotation 272–273
 - scaling 272–273
 - shape-based matching 287–292, 294, 295, 307, 371–377, 408–413, 432–438
 - similarity measure 263–267, 288–290
 - – absolute sum of normalized dot products 289
 - – normalized cross-correlation 251, 264–267, 432–438
 - – sum of absolute gray value differences 250, 263–264, 266–267
 - – sum of absolute normalized dot products 289, 307
 - – sum of normalized dot products 288–289
 - – sum of squared gray value differences 250, 263–264
 - – sum of unnormalized dot products 288
 - stopping criterion 266–267
 - – normalized cross-correlation 267
 - – sum of absolute gray value differences 266–267
 - – sum of normalized dot products 289–290
 - subpixel-accurate 271–272, 290–291
 - translation 263–271
 - temporal averaging 111–112, 142
 - temporal noise 53
 - texture
 - removal 124–125
 - thick lens 20–22
 - cardinal elements 21
 - focal length 20
 - focal point 20
 - image distance 21, 25
 - magnification 21, 27, 32, 33, 82, 86, 219
 - nodal point 21
 - object distance 21, 25

- optical axis 21, 222
 - principal plane 20
 - surface vertex 21
 - thresholding 135–138, 255, 338, 392–400, 414–425
 - automatic threshold selection 136–138, 338
 - subpixel-precise 147–149, 195, 383–388, 392–400
 - tilt lens 32–36, 82, 84, 86, 222–225, 258
 - hinge line 34
 - Scheimpflug line 33–34
 - tilted image plane 33–35, 82, 84, 86, 222–225
 - time-of-flight camera 91–95
 - continuous-wave-modulated 92–93
 - distance computation 93
 - distance range 92
 - phase demodulation 92
 - random errors 93
 - resolution 93
 - scene intensity 92
 - systematic errors 93
 - pulse-modulated 93–95
 - distance computation 93, 94
 - distance range 93
 - random errors 94–95
 - resolution 95
 - systematic errors 94–95
 - time-of-flight computation 94
 - TOF camera *see* time-of-flight camera
 - transformation
 - affine 126–127, 152, 263, 281, 288, 408–413, 432–438
 - geometric 126–134, 338, 377–383, 392–413, 432–438
 - gray value 102–104
 - image 128–134, 141, 377–383, 388–392, 408–413, 432–438
 - local deformation 292
 - perspective 127–128, 133, 224, 292, 293, 338
 - polar 133–134, 338, 377–383
 - projective 127–128, 133, 224, 263, 293, 296–298, 311, 338
 - rigid 217, 262, 273, 281, 291, 408–413
 - rigid 3D 218, 326, 329–333
 - rotation 127, 129, 152, 262, 273, 338, 400–407
 - scaling 127, 132, 152, 262, 273
 - similarity 262, 273, 281, 292, 296, 297, 305, 392–400
 - skew 127
 - slant 127
 - translation 127, 152, 160, 262, 272
 - translation-invariant operation
 - closing 170
 - opening 169
 - Transmission Control Protocol 70
 - transmittance 9
 - transposition 160–161
 - triangulation 82
 - sheet of light sensor 84
 - stereo sensor 82–83
 - structured light sensor 86
 - trigger 42, 45, 80–81
 - Tukey weight function 207
- u**
- U3V *see* USB3 Vision
 - U3VCP *see* USB3 Vision, USB3 Vision Control Protocol
 - U3VSP *see* USB3 Vision, USB3 Vision Streaming Protocol
 - UDP *see* User Datagram Protocol
 - union 159–160, 400–407
 - unit dual quaternion 330–331, 333
 - transformation matrix 331
 - unit quaternion 327–330
 - universal approximator 353, 354, 362, 365, 366
 - universal serial bus *see* USB
 - USB
 - bulk data transfers 67, 69
 - control transfers 67, 69
 - interrupt data transfers 67, 69
 - isochronous data transfers 67, 69
 - USB 2.0 67–68
 - USB3 Vision 68–69
 - U3VCP *see* USB3 Vision, USB3 Vision Control Protocol
 - U3VSP *see* USB3 Vision, USB3 Streaming Control Protocol
 - USB3 Vision Control Protocol 69
 - USB3 Vision Streaming Protocol 69
 - User Datagram Protocol 70
- v**
- variation model 141–144, 388–392, 400–407
 - vertical blanking interval 57
 - vertical overflow drain 45
 - vertical synchronization pulse 57
 - video signal
 - analog
 - back porch 57
 - CCIR 56
 - EIA-170 56
 - front porch 57
 - horizontal blanking interval 56

- – horizontal synchronization pulse 57
 - – interlaced scan 56
 - – NTSC 56
 - – PAL 56
 - – progressive scan 58
 - – vertical blanking interval 57
 - – vertical synchronization pulse 57
 - color
 - – composite video 58
 - – RGB 58
 - – S-Video 58
 - – Y/C 58
 - digital 60–72, 77–79
 - – Camera Link 61–62
 - – Camera Link HS 62–63
 - – CoaXPress 64–65
 - – FireWire *see* video signal, digital, IEEE 1394
 - – frame valid 60
 - – GenICam GenTL 65, 73, 77–79, *see* video signal, digital, GenICam GenTL standard features naming convention
 - – GenICam GenTL standard features naming convention 77–79
 - – Gigabit Ethernet *see* video signal, digital, GigE Vision
 - – GigE Vision 70–72
 - – IEEE 1394 65–66
 - – IIDC 65–66
 - – line valid 60
 - – low-voltage differential signaling 61
 - – LVDS *see* video signal, digital, low-voltage differential signaling
 - – pixel clock 60
 - – USB 2.0 67–68
 - – USB3 Vision 68–69
 - vignetting 40–41, 106
- w**
- weight decay 355–357, 368
 - weight function
 - Huber 207
 - Tukey 207
 - world coordinates
 - from sheet of light reconstruction 33, 35, 84–86, 254–257
 - – calibration 256–257
 - – extraction of laser line 255–256
 - from single image 202–203, 235–238, 256, 298
 - – line scan camera 238
 - – perspective camera 236–237
 - – telecentric camera 236
 - from stereo reconstruction 82–84, 241–254
 - from structured light reconstruction 33, 35, 86–91, 257–262
 - – camera calibration 258–261
 - – Gray code decoding 257–258
 - – phase decoding 258
 - – projector calibration 258–261
 - – radiometric calibration 261–262
 - – stripe decoding 257–258
- x**
- xenon lamp 7–8
 - XML 63, 65, 69, 71, 79
- y**
- Y/C video 58
- z**
- zero-crossing 181, 182, 195