

Index

3D cameras 48, 290

A

accelerometers 37-39, 53
Ackermann model 161
Ackerman steering 34, 35
active beacons 12, 19
active exploration 13
active vision 13, 24
Actuator dynamics 63
adaptive tessellation 259
anchoring problem 267, 293, 384
ancillary statistic 121, 122
appearance-based approaches 235
appearance-based place recognition 252, 382
approximate nearest neighbors (ANN) 198
asymptotically unbiased estimator 124
Autonomous Underwater Vehicles (AUVs) 33

B

Baron's cross-correlation coefficient 195-197, 202
Bayes, Thomas 66
Bayes Filter
 Discrete Bayes Filter (DBF) 234
Bayesian estimators 22, 110, 111, 129, 130, 133, 169, 171, 175, 203, 256, 319, 348
Bayesian network
 dynamic 204, 270
Bayesian networks (BNs) 99
Bayesian paradigm 13, 71, 96, 97
Bayes' Rule 19, 60, 97, 98, 135, 244, 270-272, 276, 277, 306, 328
Bayes' theorem 66
beam model 176-179, 226, 273, 332
bearings 16, 49, 51, 176, 180-182, 185, 198, 274, 275, 278, 285, 308
bearing-only observation 281, 284
behavior-based control architectures 17

Bernoulli distribution 257
bias of an estimator 124
biped robots 31, 32
Branch and Bound (BB) strategy 190
Bundle Adjustment (BA) 299, 364

C

cartography 15, 24, 299
casters wheels 33
central limit theorem 67, 110, 118, 142, 207, 374
central moments 82
Chebyshev's inequality 85, 86, 115, 116
chi-squared distribution 60, 81, 95, 118, 148, 188, 189
chi-squared probability distribution 188
 degrees of freedom 188
chi-squared test 68, 189
CHOLMOD algorithm 356, 378, 385
clique 101
cluttered environments 10, 323
codomain 75-78, 85, 91, 108, 190
cognitive maps 19, 25, 255, 269
complete estimator 121, 122
conditional expectation 98, 99, 106, 125, 126, 130, 131
conditional independence 98-102, 105, 175, 205, 270, 306, 307, 319-321
conditional probability 60, 64, 96-99, 122, 236, 237, 245, 319
conditional probability chain rule 97
conjugate distributions 130, 207
consistent estimator 123
constraint maps 264, 292, 294
contact sensors 17, 39
continuous random variables 75
convolution 93
countable additivity 71, 72
covariance matrix 88-91, 96, 104, 105, 109, 146,

Index

147, 154, 155, 159, 165, 168, 169, 172, 181,
185-188, 201, 208, 217, 219, 229, 280, 284,
302-304, 308, 311, 314-318, 350, 361, 378, 389
Cramér-Rao Lower Bound (CRLB) 125
cross-correlation 93, 180, 195-197, 202
cross-covariance matrix 90, 219
curse of dimensionality 243, 259
curve fitting 68

D

Data Association (DA) 263, 310
data association problem (DA) 185, 263
datasets 66-68, 111, 250
dead-reckoning 16, 19, 33, 39, 167
dead-zones 63
Decision processes 63
Deliberative robot control architectures 17
Descriptive statistics 111
developmental robotics 19, 25, 256
Differential drive 34, 156, 161
Dirac's delta 240-242, 246, 319
Discrete Bayes Filter (DBF) 234
discrete random variables 75, 234
domain 75, 76, 89, 101, 108, 190, 223, 235, 240,
277, 290
Doppler effect 38
Doppler Velocity Log (DVL) 33
drive wheels 33-35, 173
d-separation 61, 102, 276
Dynamic Bayesian Network (DBN) 204, 270
dynamic environments 11, 24, 251, 379, 380, 388
dynamic stochastic process 133

E

Effective Sample Size (ESS) 247, 322
efficient estimator 125, 126
embodied cognition 18, 23, 255, 293
engineered environments 11, 12
environmental sensors 12, 36, 52
estimator 110, 115-135, 141, 175, 222, 229, 239,
240, 302, 303, 319, 321, 342, 343, 347, 368,
374
expectation of a matrix of r.v.s 91
Exponentially Weighted Recursive Least Squares
(EW-RLS) 208
exteroceptive sensors 12, 36, 39, 40, 45, 48-51, 142,
169

F

feature descriptor 281
Field Of View (FOV) 42, 46
first-order ancillary 121, 122
Fisher information matrix 125-128
Flying Robots 32, 33, 44, 55, 143
fuzzy theory 64

G

gas sensing 51
gauge freedom 36
Gaussian Markov Random Field (GMRF) 349
Gauss-Newton algorithm 179, 299, 318, 331, 333,
336, 341, 353, 365, 368, 388, 389
Generalized Voronoi Graphs 260, 261
General Theory of Uncertainty (GTU) 64
geometrical maps 6, 93
global localization 14, 20, 205, 222, 250
Global Navigation Satellite Systems (GNSS) 12, 53
Global Positioning System 53
good old fashioned AI (GOFAI) 18
graphs 8, 61, 99-105, 108, 201, 265, 267, 276, 292,
293, 296, 301-305, 308, 315, 327, 336, 339,
348-356, 359-368, 372-378, 381-389
graphical models 60, 61, 64, 99, 135, 251, 298-300,
336
graph of correlations 61, 104, 105, 301-305, 308,
315
graph theory 99, 265, 296
greedy algorithm 187
Grid maps 39, 193-199, 202, 255-261, 264, 269,
272, 273, 290, 293, 304, 306, 318, 319, 322,
325, 332, 339, 380
ground-truth 111
gyroscopes 37-39, 171

H

Hessian matrix 330, 354-357, 361, 363, 368, 373,
376, 382
hierarchy of abstraction 268, 269
Histogram Filter (HF) 235, 238, 239
Holonomic mobile robots 151
human cognitive map 19, 269
Humanoids 31
hybrid metric-topological (HMT) maps 8, 265, 382
hybrid metric-topological SLAM 259, 293, 384
hysteresis 63

I

importance sampling 69, 240, 243, 244, 318
 inertial sensors 11, 12, 16, 33, 36-38
 inference problem with Bayesian Networks 101
 Infinite Impulse Response filter (IIR) 208
 Information Filter (IF) 209
 infrared (IR) 39
 innovation covariance 219, 220, 232, 233, 311
 interpretation tree 186, 187, 191, 200, 202
 Iterated Extended Kalman Filter 226
 Iterative Closest Point (ICP) algorithms 198

J

Jacobian structure 367
 joint compatibility 191
 Joint-Compatibility Branch and Bound (JCBB) 310
 joint probability density functions 88
 joint probability distribution 87, 103
 joint probability mass function 88

K

Kalman Filter (KF) 19, 20, 69, 105, 171, 207-211,
 215, 217, 220-223, 226, 231, 251, 252, 280,
 285, 306, 307, 321, 333, 342, 362, 363
 computational complexity 222
 Extended Kalman Filter (EKF) 207, 223, 280,
 307
 Extended Mixture Kalman Filter (EMKF) 226
 prediction stage 209, 215, 231
 residual error 222
 unscented 226, 252
 update stage 209, 217
 Kalman gain 219-224, 232, 280, 285, 312
 KD-trees 198
 kidnapped robot problem 14, 133
 Kinect™ 49, 50, 352
 kinematic designs for wheeled robots 33
 Kinematic Equations 33, 143, 151, 156, 160, 163-
 169, 173
 Kullback-Leibler divergence (KLD) 250
 kurtosis 84

L

landmark maps 254-257, 261, 263, 274, 278, 280,
 286, 290, 300, 306, 328
 landmarks 11, 14, 19, 179-184, 257-263, 274-280,
 283-286, 289, 300, 303-316, 319-324, 328-332,
 338-341, 345, 364-383

large-scale robotic mapping 19
 large-scale space 25, 252, 257, 265, 294, 295, 385
 laser scanners 20, 32, 46-48, 51, 57, 176, 332, 333,
 338, 353, 374
 law of large numbers 66, 110, 111, 115, 117, 123,
 128, 131, 132, 175, 239, 240
 learning problems with Bayesian Networks 101
 least squares estimator (LSE) 128
 least-squares minimization 341
 Legged Robots 31, 58
 Lehmann-Scheffé theorem 126
 Levenberg-Marquardt (LM) algorithms 336, 341,
 353-357, 364-368, 389
 lifelong operation 379
 likelihood field 178, 199
 Limit Laws 115
 linear correlation coefficient 90, 197
 linearization point 95, 96, 146
 line of sight 50, 177, 178, 193, 273
 lithium-ion polymer (Li-Po) 55
 localization 1-16, 19-36, 39-42, 45-51, 57, 60-70,
 80, 87, 96, 105, 106, 110-112, 120, 129, 133,
 140-144, 149, 155, 156, 167-179, 184, 185,
 195, 198-207, 222-228, 234-236, 239-245,
 248-258, 261, 263, 269, 273, 280, 284, 290,
 293-299, 307, 312, 314, 322, 333-342, 347,
 362, 379, 384-389
 local maps 174, 193-197, 293, 381-384
 log-likelihood 128, 197, 199, 389
 loop closure 257, 315, 316, 325, 326, 338-340, 361,
 368

M

machine perception and intelligent robotics group
 (MAPIR) 3
 Mahalanobis distance 185-192, 199, 201, 302, 333
 joint 191
 Manifold 149, 343-347, 356, 359-361, 386
 map matching 19, 90, 193-198, 259
 mapping 1-16, 19-32, 35, 36, 39-42, 45-48, 52, 58-
 69, 76, 80, 91, 96, 105, 106, 110-112, 120, 129,
 140, 141, 172-179, 182-186, 198-203, 207,
 251, 254-259, 263, 269, 272-275, 280, 281,
 284-287, 290-296, 299, 304, 321, 326, 334,
 335, 339, 340, 344, 352, 359, 362, 379-389
 Maritime navigation 15, 16
 Markov chains 67
 Markovian assumption 204
 Markov localization 24, 200, 235, 251, 257
 Markov property 99, 135, 291

Index

Markov random field (MRF) 99, 100, 291
Markov's inequality 85, 86
Matching Likelihood (ML) 185, 192, 198
mathematical graph 265
maximal clique 101
Maximum A Posteriori Estimator (MAP) 131
Maximum Likelihood Estimators (MLE) 302
mean squared error (MSE) 124
measure-theoretic definition of probability 69
Median Estimator (MED) 132
method of least squares 67
method of moments 110, 128
Micro Air Vehicles (MAVs) 32
MicroElectroMechanical Systems (MEMS) 12
minimal sufficient estimator 122
Minimum Mean Squared Error Estimator (MMSE)
130
minimum mismatch 352
minimum variance unbiased estimator (MVUE)
125, 222
modified environments 11
moments of a probability distribution 82
Monte Carlo localization 27, 106, 239, 251
Monte Carlo methods 20, 68, 69, 172, 239, 243,
296, 334
motion control 29
MRPT toolkit 226
multimodal distributions 80, 84, 118, 222, 287
multinomial resampling 246
Multisensory Fusion 338

N

navigation 4, 5, 10-17, 20, 24, 26, 33, 39, 53, 57, 59,
63, 64, 73, 111, 208, 255, 258-260, 264, 265,
273, 295, 338, 384, 387, 388
Nearest Neighbor DA Algorithm (NN) 187
Newton method 355, 389
non-holonomic restrictions 157
Non-parametric filters 22, 203, 207, 234, 257, 298,
303
non-repeatability of sensors 62
normal curve 66
Nouvelle AI 18

O

observation likelihood 141, 142, 175, 176, 179, 180,
193-199, 207, 217, 234-237, 241, 246, 304,
321-333, 338
occupancy grids 20, 24, 58, 177, 193, 254, 257, 258,

332, 380, 382
octomap 259, 296
octree 259
Odometry 5, 16, 24, 33-36, 39, 56-59, 140-143, 152-
173, 217, 226, 248, 327, 331, 350, 366
one-to-one function 74, 185
on-manifold optimization 354, 360, 364, 374
on-to function 75
optimal estimator 124
optimal proposal distribution 244, 327-333
optimization by relaxation 303
Outdoor scenarios 8, 10, 261
over-parameterization 284, 288, 289, 343

P

paradigms of probability 66
parametric distribution 172, 206, 332
Parametric filters 206, 207, 234, 243, 298, 303, 304,
336
partially observable 36
particle depletion problem 246
Particle Filter (PF) 239
vanilla 246
particle impoverishment 246, 327
partition function 101
passive beacons 19
paths 8, 12, 25, 33, 102-105, 186, 187, 191, 192,
295, 319, 339, 352
Perception processes 62
phase aliasing 44
pinhole projective model 283
point clouds 50, 198, 226, 248, 259, 260, 350
point maps 193, 198, 259-261, 290, 332, 353
pose 2, 6, 36, 37, 48, 67, 70, 73-75, 87, 89, 97, 111,
123, 130, 133, 135, 141-160, 163-172, 175-
186, 189, 192-195, 198-201, 205-208, 217-228,
231-240, 243-250, 255, 264, 269, 270, 276-
293, 301, 304-322, 329-333, 338-356, 359-369,
372-378, 387
pose constraint map 264
positive-definite matrix 91, 229
positive-semidefinite matrix 91, 109, 229
possibility theory 64, 106
prediction 11, 25, 106, 111, 135, 172, 181, 183, 201,
206, 209, 210, 215-218, 222, 224, 231-234,
239, 246, 251, 280, 289, 291, 309-314, 320,
330, 331, 341, 350, 351, 360
prehistoric maps 15
Probabilistic Motion Model 142-145, 150-153, 159,
165, 168-170, 236, 310, 322, 365

probability density 60, 64, 79, 88, 92, 122, 127, 129, 175, 237, 240, 241, 329
 probability function 70-72, 75, 76, 80, 91, 97, 111, 133
 probability space 69-78, 85, 87, 97, 111, 120-122, 138
 proprioceptive sensors 11, 12, 36, 140, 142, 169, 171
 pseudo-Huber kernels 375
 Pulsed-Signal Time of Flight (P-ToF) 42
 p-value 188, 189

Q

quaternions 281

R

RADAR 42, 251
 Random errors 61, 62
 random events 70-76, 89, 96, 98, 240
 random field 99, 100, 257, 290, 291, 349
 range 12, 20, 22, 28, 29, 32, 39-51, 55-58, 75, 117, 144, 147, 170, 176-181, 185, 194-200, 235, 244, 247-250, 257-263, 270-275, 278, 286, 287, 290, 292, 295, 296, 308, 312, 332, 335, 337, 342, 379, 381, 384, 387, 388
 range-bearing sensors 12, 51, 176, 179, 278, 279, 283, 330
 rangefinders 40-45, 48
 Range-Only Sensors 49-51, 254, 286, 304, 365
 Rao-Blackwellization, general theory of 69, 126, 303, 318
 Rao-Blackwellization Particle Filter (RBPF) 182, 318, 334
 Rao-Blackwell theorem 126
 raw moments 82
 ray-casting 176, 177
 Real-time Kinematics (RTK) 53
 Real World Interface (RWI) 156
 reduced linear system 369
 reflectivity sensors 39, 40
 Relative Bundle Adjustment (RBA) 378
 RFID tags 53
 right-tail of a pdf 189
 rigid transformation 19, 193, 388
 risk of an estimator 124
 robot actions 22, 29, 30, 35, 140, 141, 175, 303
 robot awakening problem 14, 222, 234
 robotic data set 13
 robotic manipulators 1-4, 16
 robust estimator 123, 374

robustified cost function 375

S

sample space 70-78, 85, 91, 108
 sample variance 110, 118, 129
 Sampling Importance 246
 saturation 272
 Scalability 23, 336, 340, 381, 383
 Schur complements 370, 371
 semantic maps 24, 265, 268, 294, 386
 sensor fusion 171
 sensor linearity 61
 sensor model
 inverse 272-274, 278, 279, 282-284, 287, 288, 313, 314
 sensor resolution 61, 63
 sequential Bayesian filtering 135
 sequential estimation 106, 130, 169, 250, 325, 333, 384
 Sequential Importance Sampling (SIS) algorithm 243
 Sequential Monte Carlo (SMC) estimation 239
 Settling times 63
 sigma-point filtering 228
 sigma-points 229-232
 simultaneity of random events 70, 71
 simultaneous localization and mapping (SLAM) 35, 48, 106, 112
 back-end 352
 EKF-based 309, 313, 315, 322, 324, 339, 342, 346, 353, 378, 380
 front-end 352
 full 298-305, 318-325, 338, 348, 349, 364, 365
 graph 292, 336, 348-356, 361-367, 372-378, 382, 383, 388, 389
 graph-SLAM approaches 264
 hybrid metric-topological 259, 293, 384
 large-scale 20
 on-line 304-308, 314-318, 323
 skewness 84
 SLAM problem 14, 180, 187, 193, 255, 276, 301, 318, 320, 336, 341, 349, 372, 378, 389
 sonars 42-45, 176
 sources of uncertainty 61, 63, 177, 178, 324
 sparse Cholesky algorithm 355, 356
 Spatial Semantic Hierarchy 25, 269, 295, 296
 squared Mahalanobis distance (SMD) 185
 squared weighted residuals 302
 Square Root Information Filtering (SRIF) 363
 Square Root Information Smoothing 363

Index

stability-plasticity dilemma 379
standardized moments 82
standard proposal distribution 245, 323, 327
State Space Model (SSM) 208
state space topology 341
static workspaces 11
statistical inference 29, 95, 107, 111
Statistics 6, 19-22, 26, 60, 64-68, 90, 106, 107, 110-117, 120, 137, 171, 189, 251, 269, 334, 386
stereo camera 51, 263
stochastic process 67-76, 108, 111-120, 126, 133, 136
strong law of large numbers 117
strongly consistent estimator 123
Structured-light cameras 49
structured scenarios 8
Structure From Motion (SFM) 299
submaps 193
Submarine Robots 33
sub-symbolic maps 256, 264
sufficient estimator 122
sum of Gaussians (SOG) 288
symbol grounding problem 256, 265, 267, 294
symbolic maps 256, 265-269
Synchro drive 35
Systematic errors 61, 142, 152

T

Taylor series expansion 95, 146, 168, 181, 311, 354, 358, 389
theorem of total probability 97
theory of probability 64, 65, 71
Time-of-Flight (ToF) 40

topological map 8, 75, 264, 265, 268, 381
 hybrid metrical 8, 265
topological relations 256, 264, 269
tracking problem 13, 14
Tree-based network optimizer (TORO) 261, 295, 363, 364
tricycle model 34, 161, 162

U

Ultra Wide Band (UWB) 50
unbiaseness 116
uncertainty inflation 175
 overestimation 175
 underestimation 175
unimodal distributions 80
unmanned aerial vehicles (UAV) 32
Unscented Kalman Filter 226, 252
Unscented Transformation 96, 318
Unscented Transform (UT) 228

V

Valve-Regulated Lead-Acid (VRLA) 55
Vented Lead-Acid (VLA) 55
view-based maps 264, 294
visual servoing 29
voxels 257

W

weak law of large numbers 115
weakly consistent estimator 123
wheeled-robot odometry 33
Wheeled robots 22, 32-35, 140, 341
working ranges 61, 63