

Contents

1	Introduction	1
1.1	The Historical Context	1
1.2	The Contents of the Book	4
1.3	Software	7
1.4	The Aims of the Book	8

Part I Recursive Estimation of Parameters in Linear Regression Models

2	Recursive Estimation: A Simple Tutorial Introduction	13
2.1	Recursive Estimation of the Mean Value of a Random Variable	15
2.1.1	Filtering interpretation of the recursive algorithm	20
2.2	Recursive Least Squares Estimation for a Single Unknown Parameter	21
2.3	Exercises	26
2.4	Summary	27
3	Recursive Least Squares Estimation	29
3.1	The Deterministic Recursive Linear Least Squares Algorithm	30
3.2	The Stochastic Recursive Linear Least Squares Algorithm	34
3.3	Some Cautionary Comments: Multiple Collinearity and Errors-in-Variables	40
3.3.1	Multiple collinearity	41
3.3.2	Errors-in-variables, the structural model and instrumental variable estimation	42
3.4	Connection with Stochastic Approximation	45
3.5	Exercises	45
3.6	Summary	45

4	Recursive Estimation of Time Variable Parameters in Regression Models	47
4.1	Shaping the Memory of the Estimator	50
4.1.1	The moving Rectangular Window (RW)	50
4.1.2	The moving Exponentially-Weighted-Past (EWP) window	53
4.2	Modelling the Parameter Variations	59
4.2.1	The complete TVP regression model	67
4.3	Vector Measurements	69
4.4	The Kalman Filter	71
4.5	Recursive Fixed-Interval Smoothing	76
4.5.1	Simple FIS estimation	77
4.5.2	Optimal FIS algorithms	78
4.5.3	Optimization of hyper-parameters	81
4.5.4	Implementation of the KALMSMO algorithm	82
4.5.5	The physical nature of FIS estimation	85
4.6	Final Recursive Analysis of the Walgett Data	86
4.6.1	Statistical methods for detecting the presence of parameter variation	88
4.7	Simplified Constant Gain Algorithms for Time Variable Parameter Estimation	92
4.8	The Estimation of Rapidly Varying Parameters	94
4.9	Variance Intervention	96
4.10	Exercises	97
4.11	Summary	98
5	Unobserved Component Models	99
5.1	The Dynamic Linear Regression (DLR) Model	102
5.1.1	Example: DLR analysis of LIDAR data	103
5.2	The Dynamic Harmonic Regression (DHR) Model and Time Series Forecasting	106
5.2.1	Spectral analysis of the DHR model	109
5.2.2	The complete DHR estimation algorithm	114
5.2.3	Practical example: Signals Passed At Danger (SPAD) data	115
5.2.4	Extensions of DHR model analysis	121
5.3	The Dynamic AutoRegression (DAR) Model and Time-Frequency Analysis	121
5.3.1	Practical example: palaeoclimatic data analysis	122
5.4	Dynamic ARX and FIR Models	128
5.4.1	Example: DARX model estimation	131
5.5	Forecasting with UC models	134
5.6	Exercises	136
5.7	Summary	136

Part II Recursive Estimation of Parameters in Transfer Function Models

6	Transfer Function Models and the Limitations of Recursive Least Squares	139
6.1	Introduction: Direct Estimation of the State Space Model	140
6.2	From State Space to Observation Space	141
6.3	Least Squares Estimation: Its Advantages and Limitations	150
6.4	Least Squares Estimation: ARX Model Estimation	154
6.4.1	Example 6.1: Estimation of a simple ARX model	155
6.5	Least Squares Estimation: FIR Model Estimation	162
6.5.1	Example 6.2: Estimation of a simple FIR model	163
6.6	Identifiability	164
6.6.1	Choice of input signals	166
6.6.2	Restrictions on the system to be identified	168
6.6.3	The more general case	168
6.6.4	Noise process identifiability	169
6.6.5	Some concluding comments on identifiability	169
6.7	Recursive Estimation of Transfer Function Models	170
6.8	Standard Instrumental Variable (SIV) Estimation	171
6.8.1	Statistical properties of SIV estimates	174
6.9	Model Structure Identification	176
6.9.1	Example 6.3: Recursive SIV parameter estimation for a simple TF model	179
6.9.2	Example 6.4: SIV estimation of tracer experiment data	181
6.10	Dynamic Transfer Function Models	185
6.10.1	Example 6.5: DTF model estimation	188
6.10.2	Example: Using DTF estimation for model diagnosis	189
6.11	Multivariable Transfer Function Models	192
6.12	Exercises	194
6.13	Summary	195
7	Optimal Identification and Estimation of Discrete-Time Transfer Function Models	197
7.1	Refined Instrumental Variable Estimation	200
7.1.1	Recursive-iterative instrumental variable estimation	200
7.1.2	The system TF estimation model and RIV estimation	202
7.1.3	The ARMA noise estimation model and IVARMA estimation	204
7.2	The Recursive-Iterative Algorithms	207
7.2.1	Implementation of the RIV and SRIV algorithms	208
7.2.2	Convergence of the iterative algorithms	209
7.2.3	Theoretical justification of the RIV method	210
7.3	Model Structure Identification	212
7.4	Input Noise and Errors-in-Variables	213
7.4.1	Example 7.1: Errors-in-Variables: the effects of input noise	216

7.5	Examples of RIV Identification and Estimation: SISO Models	220
7.5.1	Example 7.2: Discrete-time simulation example 1	220
7.5.2	Example 7.3: Discrete-time simulation example 2	222
7.5.3	Example 7.4: Evaluating over-parameterization	224
7.5.4	Example 7.5: RIV estimation of tracer experiment data	225
7.6	MISO Model Estimation	227
7.7	Examples of SRIVDD Identification and Estimation for MISO Models	231
7.7.1	Example 7.6: Simulation results for a 3-input MISO model	231
7.7.2	Example 7.7: SRIVDD modelling of a MISO winding process	233
7.7.3	Example 7.8: SRIVDD evaluation: Monte Carlo simulation results	236
7.8	Optimal Prefilters and an Adaptive Kalman Filter	237
7.9	Exercises	238
7.10	Summary	239
8	Optimal Identification and Estimation of Continuous-Time Transfer Function Models	241
8.1	Introduction	241
8.2	TF Conversion Between Continuous and Discrete-Time	243
8.3	Hybrid Continuous-Time RIVC Estimation	244
8.4	The Iterative RIVC and SRIVC Algorithms	248
8.5	Model Structure Identification and MISO Model Estimation	250
8.6	Examples of RIVC Identification and Estimation	251
8.6.1	Example 7.1: Continuous-time simulation example	251
8.6.2	Example 7.2: RIVC SISO estimation of tracer experiment data	254
8.6.3	Example 7.3: SRIVCDD MISO modelling of the tracer experiment data	256
8.6.4	Example 7.4: Evaluation of a Global Circulation Model	261
8.7	Sampling Considerations	264
8.7.1	The effects of sampling interval on estimation accuracy	265
8.8	Exercises	268
8.9	Summary and Conclusions	269
9	Identification of Transfer Function Models in Closed-Loop	271
9.1	Introduction	271
9.2	The Generalized Box-Jenkins Model in a Closed-Loop Context . . .	272
9.3	Closed-Loop Identification and Estimation	274
9.3.1	Simple CLSRIV and CLSRIVC two-stage closed- loop estimation	274
9.3.2	Three-stage CLRIV and CLRIVC closed-loop estimation	275
9.3.3	Unstable systems	276

9.4	Simulation Examples	277
9.4.1	Example 9.1: Closed-loop, stable, discrete-time system estimation	278
9.4.2	Example 9.2: Closed-loop, stable, continuous-time system estimation	280
9.4.3	Example 9.3: Closed-loop, unstable and marginally stable system estimation	283
9.5	Exercises	286
9.6	Summary and Conclusions	287
10	Real-Time Recursive Parameter Estimation	289
10.1	Prediction Error (PE) Methods and the RPEM Algorithm	290
10.1.1	Statistical Properties of the PEM Estimates for the BJ Model	295
10.2	Real-Time Recursive RRIV Estimation	297
10.2.1	The recursive algorithms	297
10.2.2	Implementation	299
10.2.3	Example 10.1: RSRIV estimation of TVPs in a simulated 2 nd order TF model	301
10.3	The Extended Kalman Filter	304
10.3.1	The EKF in a recursive prediction error form	310
10.4	Computationally Intensive Methods of Recursive Estimation	311
10.5	Example 12.1: Data Assimilation and Adaptive Forecasting	315
10.5.1	The DBM model	316
10.5.2	Parameter updating by RRIV estimation	319
10.5.3	State updating by the Kalman Filter	320
10.5.4	Typical adaptive forecasting results	320
10.6	Exercises	322
10.7	Summary	323
 Part III Other Topics		
11	State-Dependent Parameter (SDP) Estimation	327
11.1	Introduction	327
11.2	SDP Identification of Nonlinear Input-Output Systems	329
11.2.1	Full SDP estimation	331
11.2.2	Parameterization and final nonlinear model estimation	335
11.2.3	The problem of Errors-in-Variables (EIV) estimation	338
11.3	SDP Identification of Purely Stochastic Nonlinear Systems	345
11.4	SDP Estimation in Hydrology	352
11.5	SDP Estimation in Forecasting and Automatic Control	352
11.6	Exercises	353
11.7	Summary and Conclusions	354

12	Data-Based Mechanistic (DBM) Modelling	357
12.1	Introduction	357
12.2	A brief Review of Data-Based Mechanistic Modelling	359
12.3	Model Order Reduction	362
12.3.1	The ALSTOM gasifier example	363
12.4	Large Computer Model Emulation	365
12.5	An Illustrative Example: DBM Modelling of Pollution Transport in a Wetland Area	367
12.5.1	The large simulation model	368
12.5.2	Emulation modelling	372
12.5.3	Modelling from real data	375
12.6	Exercises	380
12.7	Conclusions	380
	Epilogue	382
A	The K. F. Gauss Derivation of Recursive Least Squares	389
B	Basic Mathematical and Statistical Background	397
B.1	Matrix Algebra	397
B.1.1	Matrices	397
B.1.2	Vectors	398
B.1.3	Matrix Addition (or Subtraction)	398
B.1.4	Matrix or Vector Transpose	398
B.1.5	Matrix Multiplication	399
B.1.6	Determinant of a Matrix	400
B.1.7	Partitioned Matrices	401
B.1.8	Inverse of a Matrix	402
B.1.9	Quadratic Forms	403
B.1.10	Positive Definite or Semi-Definite Matrices	403
B.1.11	The Rank of a Matrix	403
B.1.12	Differentiation of Vectors and Matrices	403
B.1.13	Cholesky Decomposition	405
B.1.14	Singular Value Decomposition (SVD)	406
B.2	Statistics and Probability	407
B.2.1	Discrete Random Variables	407
B.2.2	Law of large Numbers	408
B.2.3	Discrete Random Vectors	408
B.2.4	Conditional Probabilities	409
B.2.5	Continuous Random Variables and Vectors	410
B.2.6	The Normal or Gaussian Density Function	410
B.2.7	Properties of Estimators	411
B.2.8	The Likelihood Function and Maximum Likelihood Estimation	412

B.2.9	The Cramer-Rao Lower Bound	414
B.2.10	Maximum Likelihood Estimators: the Vector Case	414
B.3	Time Series	415
B.3.1	Gauss-Markov Random Processes	417
B.3.2	The State Space Model of a Linear, Discrete-time, Stochastic Dynamic System	418
B.3.3	The Discrete-Time Transfer Function Model	419
B.3.4	Continuous-time, Stochastic Dynamic Models	423
B.3.5	Hybrid Stochastic Dynamic Models	424
B.3.6	Multivariable (Multi-Input, Multi-Output) TF Models	426
B.3.7	Physical Interpretation of TF Models	427
B.3.8	Differentiation of a TF with Respect to a Given Parameter	439
B.3.9	A Simple Introduction to Monte Carlo Simulation	439
C	Stochastic Approximation	445
C.1	Some Extensions to Stochastic Approximation	451
C.1.1	Matrix gain SA and optimum algorithms	451
C.1.2	Continuous-time algorithms	452
C.1.3	Search algorithms	453
C.1.4	Acceleration of convergence	453
C.2	Summary	454
D	Deterministic Regularization and Stochastic Fixed Interval Smoothing	455
D.1	Wiener-Kolmogorov-Whittle Optimal Signal Extraction	457
E	The Instantaneous Cost Function Associated with the Recursive Least Squares Algorithm	461
F	Maximum Likelihood Derivation of the Refined Instrumental Variable Algorithm	465
F.1	RIV System Model Estimation Within the Context of Maximum Likelihood	467
G	The CAPTAIN Toolbox for Matlab: an Overview	469
	Glossary	473
	References	477
	Index	499