

# Contents

## Part I Introduction, Basic Concepts and Preliminaries

<b>1</b>	<b>Introduction</b>	3
1.1	Basic Concepts	3
1.2	Motivation	5
1.2.1	Data-Driven and Model-Based FDI	5
1.2.2	Fault-Tolerant Control and Lifetime Management	5
1.2.3	Information Infrastructure	6
1.3	Outline of the Contents	7
1.4	Notes and References	9
	References	10
<b>2</b>	<b>Case Study and Application Examples</b>	11
2.1	Three-Tank System	11
2.1.1	Process Dynamics and Its Description	11
2.1.2	Description of Typical Faults	13
2.1.3	Closed-Loop Dynamics	14
2.2	Continuous Stirred Tank Heater	15
2.2.1	Plant Dynamics and Its Description	15
2.2.2	Faults Under Consideration	17
2.3	An Industrial Benchmark: Tennessee Eastman Process	17
2.3.1	Process Description and Simulation	17
2.3.2	Simulated Faults in TEP	20
2.4	Notes and references	21
	References	21
<b>3</b>	<b>Basic Statistical Fault Detection Problems</b>	23
3.1	Some Elementary Concepts	23
3.1.1	A Simple Detection Problem and Its Intuitive Solution	23
3.1.2	Elementary Concepts in Fault Detection	24
3.1.3	Problem Formulations	26
3.2	Some Elementary Methods and Algorithms	26
3.2.1	The Intuitive Solution	26

3.2.2	$T^2$ Test Statistic . . . . .	27
3.2.3	Likelihood Ratio and Generalized Likelihood Ratio . . . . .	28
3.2.4	Vector-Valued GLR . . . . .	29
3.3	The Data-Driven Solutions of the Detection Problem . . . . .	31
3.3.1	Fault Detection with a Sufficiently Large $N$ . . . . .	32
3.3.2	Fault Detection Using Hotelling's $T^2$ Test Statistic. . . . .	33
3.3.3	Fault Detection Using $Q$ Statistic . . . . .	35
3.4	Case Example: Fault Detection in Three-Tank System . . . . .	36
3.4.1	System Setup and Simulation Parameters . . . . .	36
3.4.2	Training Results and Threshold Setting. . . . .	37
3.4.3	Fault Detection Results . . . . .	39
3.5	Variations of the Essential Fault Detection Problem . . . . .	44
3.5.1	Variation I. . . . .	44
3.5.2	Variation II . . . . .	45
3.6	Notes and References . . . . .	46
	References . . . . .	47
<b>4</b>	<b>Fault Detection in Processes with Deterministic Disturbances. . . . .</b>	<b>49</b>
4.1	Problem Formulations and Some Elementary Concepts. . . . .	49
4.1.1	A Simple Detection Problem and Its Intuitive Solution. . . . .	49
4.1.2	Some Essential Concepts. . . . .	50
4.1.3	Problem Formulations. . . . .	52
4.2	Some Elementary Methods and Algorithms . . . . .	53
4.2.1	An Intuitive Strategy. . . . .	53
4.2.2	An Alternative Solution. . . . .	54
4.2.3	A Comparison Study. . . . .	56
4.2.4	Unknown Input Estimation Based Detection Scheme. . . . .	57
4.2.5	A General Solution. . . . .	58
4.3	A Data-Driven Solution of the Fault Detection Problem . . . . .	60
4.4	A Variation of the Essential Fault Detection Problem. . . . .	62
4.5	Case Study . . . . .	64
4.5.1	Case Study on Laboratory System CSTD . . . . .	64
4.5.2	Case Study on Three-Tank System . . . . .	67
4.6	Notes and References . . . . .	68
	References . . . . .	70

## Part II Application of Multivariate Analysis Methods to Fault Diagnosis in Static Processes

<b>5</b>	<b>Application of Principal Component Analysis to Fault Diagnosis.</b>	73
5.1	The Basic Application Form of PCA to Fault Detection	73
5.1.1	Algorithms.	74
5.1.2	Basic Ideas and Properties.	75
5.2	The Modified Form of <i>SPE</i> : Hawkin's $T_H^2$ Statistic	77
5.3	Fault Sensitivity Analysis	78
5.3.1	Sensitivity to the Off-set Faults	79
5.3.2	Sensitivity to the Scaling Faults	80
5.4	Multiple Statistical Indices and Combined Indices	81
5.5	Dynamic PCA	84
5.6	Fault Identification	84
5.6.1	Identification of Off-set Faults	84
5.6.2	Identification of Scaling Faults.	85
5.6.3	A Fault Identification Procedure.	86
5.7	Application to TEP.	87
5.7.1	Case Study on Fault Scenario 4	87
5.7.2	Case Study Results for the Other Fault Scenarios.	89
5.7.3	Comparison of Multiple Indices with Combined Indices	90
5.8	Notes and References	93
	References	93
<b>6</b>	<b>Application of Partial Least Squares Regression to Fault Diagnosis.</b>	95
6.1	Partial Least Squares Algorithms	95
6.2	On the PLS Regression Algorithms	98
6.2.1	Basic Ideas and Properties.	98
6.2.2	Application to Fault Detection and Process Monitoring.	101
6.3	Relations Between LS and PLS	103
6.3.1	LS Estimation	103
6.3.2	LS Interpretation of the PLS Regression Algorithm	105
6.4	Remarks on PLS Based Fault Diagnosis	110
6.5	Case Study on TEP.	111
6.5.1	Test Setup	111
6.5.2	Offline Training	111
6.5.3	Online Running	111
6.6	Notes and References	116
	References	116

<b>7</b>	<b>Canonical Variate Analysis Based Process Monitoring and Fault Diagnosis</b>	117
7.1	Introduction to CCA	117
7.2	CVA-Based System Identification	119
7.3	Applications to Process Monitoring and Fault Detection	123
7.3.1	Process Monitoring	123
7.3.2	Fault Detection Schemes	124
7.4	Case Study: Application to TEP	126
7.4.1	Test Setup and Training	126
7.4.2	Test Results and a Comparison Study	127
7.5	Notes and References	128
	References	131

### Part III Data-driven Design of Fault Diagnosis Systems for Dynamic Processes

<b>8</b>	<b>Introduction, Preliminaries and I/O Data Set Models</b>	135
8.1	Introduction	135
8.2	Preliminaries and Review of Model-Based FDI Schemes	136
8.2.1	System Models	136
8.2.2	Model-Based Residual Generation Schemes	140
8.3	I/O Data Models	148
8.4	Notes and References	150
	References	151
<b>9</b>	<b>Data-Driven Diagnosis Schemes</b>	153
9.1	Basic Concepts and Design Issues of Fault Diagnosis in Dynamic Processes	153
9.2	Data-Driven Design Schemes of Residual Generators	154
9.2.1	Scheme I	154
9.2.2	Scheme II	155
9.2.3	Scheme III	157
9.2.4	A Numerically Reliable Realization Algorithm	159
9.2.5	Comparison and Discussion	161
9.3	Test Statistics, Threshold Settings and Fault Detection	162
9.4	Fault Isolation and Identification Schemes	162
9.4.1	Problem Formulation	163
9.4.2	Fault Isolation Schemes	165
9.4.3	Fault Identification Schemes	166
9.5	Case Study: Fault Detection in Three-Tank System	167
9.5.1	System and Test Setup	168
9.5.2	Test Results	168
9.5.3	Handling of Ill-Conditioning $\Sigma_{res}$	169

9.6	Notes and References . . . . .	172
	References . . . . .	173
<b>10</b>	<b>Data-Driven Design of Observer-Based Fault Diagnosis Systems.</b> . . . .	175
10.1	Motivation and Problem Formulation . . . . .	175
10.2	Parity Vectors Based Construction of Observer-Based Residual Generators . . . . .	175
10.2.1	Generation of a Scalar Residual Signal . . . . .	176
10.2.2	Generation of $m$ -Dimensional Residual Vectors . . . . .	178
10.2.3	Data-Driven Design of Kalman Filter Based Residual Generators . . . . .	182
10.3	Fault Detection, Isolation and Identification. . . . .	184
10.3.1	On Fault Detection . . . . .	184
10.3.2	Fault Isolation Schemes. . . . .	185
10.3.3	A Fault Identification Scheme . . . . .	186
10.4	Observer-Based Process Monitoring . . . . .	187
10.5	Case Study on CSTDH . . . . .	188
10.5.1	System Setup . . . . .	188
10.5.2	Towards the Kalman Filter-Based Residual Generator . . . . .	189
10.5.3	Towards the Generation of $m$ -Dimensional Residual Vectors . . . . .	190
10.6	Case Study on TEP. . . . .	194
10.7	Remarks on the Application of the Data-Driven FDI Systems . . . . .	197
10.8	Notes and References . . . . .	198
	References . . . . .	199

**Part IV Adaptive and Iterative Optimization Techniques for Data-driven Fault Diagnosis**

<b>11</b>	<b>Adaptive Fault Diagnosis Schemes</b> . . . . .	203
11.1	OI-based Recursive SVD Computation and Its Application . . . . .	203
11.1.1	Problem Formulation . . . . .	204
11.1.2	DPM: An Adaptive Algorithm . . . . .	204
11.1.3	Applications to Fault Detection . . . . .	205
11.2	An Adaptive SVD Algorithm and Its Applications . . . . .	206
11.2.1	The Adaptive SVD Algorithm . . . . .	206
11.2.2	Applications to Fault Detection . . . . .	208
11.3	Adaptive SKR Based Residual Generation Method. . . . .	208
11.3.1	Problem Formulation . . . . .	209
11.3.2	The Adaptive Residual Generation Algorithm . . . . .	210

11.3.3	Stability and Exponential Convergence . . . . .	211
11.3.4	An Extension to the Adaptive State Observer . . . . .	214
11.4	Case Studies . . . . .	215
11.4.1	Application of Adaptive SVD Based RPCA Scheme to Three-Tank System. . . . .	215
11.4.2	Application of the Adaptive Observer-Based Residual Generation Scheme to the Three-Tank System . . . . .	218
11.5	Notes and References . . . . .	221
	References . . . . .	222
<b>12</b>	<b>Iterative Optimization of Process Monitoring and Fault Detection Systems.</b> . . . .	223
12.1	Iterative Generalized Least Squares Estimation . . . . .	223
12.2	Iterative RLS Estimation . . . . .	225
12.2.1	The Basic Idea and Approach . . . . .	225
12.2.2	Algorithm, its Realization and Implementation. . . . .	227
12.2.3	An Example. . . . .	227
12.3	Iterative Optimization of Kalman Filters . . . . .	231
12.3.1	The Idea and Scheme . . . . .	231
12.3.2	Algorithm and Implementation. . . . .	235
12.3.3	An Example. . . . .	236
12.4	Case Study . . . . .	237
12.4.1	Case 1: $\Sigma_v$ is Unknown While $\Sigma_w$ is Given . . . . .	239
12.4.2	Case 2: $\Sigma_w$ is Unknown While $\Sigma_v$ is Given . . . . .	240
12.5	Notes and References . . . . .	241
	References . . . . .	243
<b>Part V</b>	<b>Data-driven Design and Lifetime Management of Fault-tolerant Control Systems</b>	
<b>13</b>	<b>Fault-Tolerant Control Architecture and Design Issues . . . . .</b>	247
13.1	Preliminaries . . . . .	247
13.1.1	Image Representation and State Feedback Control . . . . .	248
13.1.2	Parametrization of Stabilizing Controllers . . . . .	249
13.2	Fault-Tolerant Control Architecture and Relevant Issues . . . . .	250
13.2.1	An Observer-Based Fault-Tolerant Control Architecture . . . . .	250
13.2.2	Design and Optimal Settings . . . . .	252
13.2.3	A Residual-Based Fault-Tolerant and Lifetime Management Structure . . . . .	255
13.2.4	System Dynamics and Design Parameters . . . . .	257
13.3	Notes and References . . . . .	261
	References . . . . .	262

<b>14</b>	<b>Data-Driven Design of Observer-Based Control Systems . . . . .</b>	<b>263</b>
14.1	Problem Formulation . . . . .	263
14.2	Data-Driven Realization Form of the Image Representation. . .	264
14.3	An Identification Scheme for the Image Representation . . . . .	266
14.3.1	A Brief Review of the I/O Data Set Model and Relevant Issues . . . . .	266
14.3.2	The Identification Scheme . . . . .	266
14.4	A data-Driven Design Scheme of Observer-Based Control Systems . . . . .	271
14.4.1	Data-Driven Design of Feed-Forward Controller . . . . .	271
14.4.2	Observer-Based State Feedback Controller Design . . .	272
14.5	Concluding Remarks . . . . .	274
14.6	Experimental Study on Laboratory CSTD System . . . . .	275
14.6.1	System Setup and Process Measurements . . . . .	275
14.6.2	Towards the Observer-Based Controller Design . . . . .	275
14.6.3	Towards the Fault-Tolerant Control Scheme . . . . .	276
14.7	Notes and References . . . . .	277
	References . . . . .	279
<b>15</b>	<b>Realization of Lifetime Management of Automatic Control Systems . . . . .</b>	<b>281</b>
15.1	Adaptive Update of H-PRIO Parameters . . . . .	281
15.1.1	Problem Formulation . . . . .	282
15.1.2	Basic Idea . . . . .	283
15.1.3	The Adaptive Scheme . . . . .	284
15.1.4	Realization of the Adaptive Scheme . . . . .	286
15.2	Iterative Update of L-PRIO Parameters . . . . .	287
15.2.1	Problem Formulation . . . . .	287
15.2.2	Iterative Solution Algorithm . . . . .	289
15.3	Implementation of the Lifetime Management Strategy . . . . .	290
15.3.1	A General Description. . . . .	290
15.3.2	Case Study on Three-Tank System . . . . .	291
15.4	Notes and References . . . . .	296
	References . . . . .	297
	<b>Index . . . . .</b>	<b>299</b>

<http://www.springer.com/978-1-4471-6409-8>

Data-driven Design of Fault Diagnosis and  
Fault-tolerant Control Systems

Ding, S.X.

2014, XX, 300 p. 106 illus., 101 illus. in color.,

Hardcover

ISBN: 978-1-4471-6409-8