Contents

Part I Co-modelling and Co-simulation: The Technical Basis

1	Conad	orative Development of Embedded Systems	3
	Marcel	Verhoef, Kenneth Pierce, Carl Gamble,	
	and Jar	n Broenink	
	1.1	Introduction	3
	1.2	Setting the Scene	4
	1.3	The Embedded Systems Design Challenge	8
	1.4	Embedded Systems Design: An Illustrative Story	10
	1.5	A Solution: The Crescendo Approach	13
	1.6	Conclusion	14
2	Co-mo	delling and Co-simulation in Embedded Systems Design	15
	John F	itzgerald and Kenneth Pierce	
	2.1	Introduction	15
	2.2	Systems and System Boundaries	15
	2.3	Models	16
	2.4	Co-models	17
	2.5	Co-simulation	19
	2.6	DSE and Automated Co-model Analysis	21
	2.7	Co-simulation in Practice	22
	2.8	Conclusion	25
3	Contir	nuous-Time Modelling in 20-sim	27
	Job va	n Amerongen, Christian Kleijn, and Carl Gamble	
	3.1	Introduction	27
	3.2	Physical Systems	29
	3.3	Icons and Iconic Diagrams	34
	3.4	A Domain-Independent Description: Bond Graphs	36
	3.5	Simulating Physical Systems with 20-sim	46
	3.6	Control Systems	49

xvi Contents

	.7 A Small Note on Notation	58 59		
4	Discrete-Event Modelling in VDM	61		
•	eter Gorm Larsen, John Fitzgerald, Marcel Verhoef,	01		
	and Kenneth Pierce			
	.1 Introduction	61		
	.2 Basic Elements: Data and Functionality	63		
	.3 Example: A Basic Controller Model	72		
	.4 Modelling with Structured Data	73		
	.5 Example: Supervisory Control	81		
	.6 Example: Controlling for Safety	84		
	.7 Object-Oriented Structuring	87		
	.8 Concurrency	91		
	.9 Modelling Systems	93		
	.10 Conclusion	95		
5	Support for Co-modelling and Co-simulation: The			
	Crescendo Tool	97		
	Peter Gorm Larsen, Carl Gamble, Kenneth Pierce,			
	Augusto Ribeiro, and Kenneth Lausdahl			
	Introduction	97		
	Importing the Torsion Bar Co-model	98		
	Crescendo Contracts	98		
	Starting a Co-simulation	104		
	Using Scripts and SDPs	108		
	Changing the Torsion Bar Model	109		
	Conclusion	114		
6	Co-model Structuring and Design Patterns	115		
	Kenneth Pierce, Peter Gorm Larsen, and John Fitzgerald			
	5.1 Introduction	115		
	Object-Orientation and Inheritance	117		
	Interfaces for Sensors and Actuators	119		
	5.4 Design Patterns	121		
	Using Inheritance for Threads			
	Structuring Constituent Models for Flexible Simulation	131		
	5.7 Conclusion	137		
Par	II Methods and Applications: The Pragmatics of			
ıaı	Co-modelling and Co-simulation			
7	Case Studies in Co-modelling and Co-simulation	141		
•	Marcel Verhoef, Bert Bos, Kenneth Pierce, Carl Gamble,	. 11		
	and Job van Amerongen			
	7.1 Introduction	141		
	7.2 The R2-G2P Line-Following Robot	142		

Contents

xvii

	7.3 7.4	The ChessWay Self-balancing Scooter	145 151
8		ds for Creating Co-models of Embedded Systems	153
	Kennet 8.1	h Pierce, Sune Wolff, and Marcel Verhoef Introduction	153
	8.2	Paths to Co-models	153
	8.3		157
	8.4	Using SysML Initially The CT-first Approach	164
	8.5	The DE-first Approach	171
	8.6	The Contract-first Approach	182
	8.7	Conclusion	183
9	Co-mo	delling of Faults and Fault Tolerance Mechanisms	185
		amble, Kenneth Pierce, John Fitzgerald, and Bert Bos	
	9.1	Introduction	185
	9.2	Fault Identification	186
	9.3	Fault Selection	188
	9.4	Fault Modelling	188
	9.5	Fault Tolerance Coverage	190
	9.6	Fault Tolerance Modelling	190
	9.7	An Example Using the Line-Following Robot	190
	9.8	An Example Using the ChessWay	194
	9.9	Conclusion	197
10		Space Exploration for Embedded Systems Using	
		nulation	199
		amble and Kenneth Pierce	
	10.1	Introduction	199
	10.2	Using ACA	200
	10.3	An Example Using the Line-Following Robot	202
	10.4	Candidate Parameters	205
	10.5	Experimental Design	207
	10.6	Using Folder Launch Configuration	210
	10.7	An Example Using the T1X Tractor	211
	10.8	Ranking of Results	216
	10.9	An Example Using the Line-Measuring Robot	218
	10.10	Conclusion	222
11	Industrial Application of Co-modelling		
		o-simulation Technology	223
		l Verhoef and Peter Gorm Larsen	
	11.1	Introduction	223
	11.2	A Dredging Excavator	225
	11.3	A Document Handling System	237
	11.4	The ChessWay Self-balancing Scooter	253
	11.5	Conclusion	258

xviii Contents

Part III Advanced Topics

12		ying Co-modelling in Commercial Practice	263
	Sune V	Wolff, Peter Gorm Larsen, and Marcel Verhoef	
	12.1	Introduction	263
	12.2	Company Introductions	264
	12.3	Traditional Development	264
	12.4	Integrating Co-modelling and Co-simulation	
		with Existing Processes	265
	12.5	Resources	266
	12.6	Challenges Encountered	266
	12.7	Key Benefits	267
	12.8	The Future of Co-modelling	269
	12.9	Conclusion	270
12	C		
13		ntics of Co-simulation	273
	•	W. Coleman, Kenneth Lausdahl, and Peter Gorm Larsen	070
	13.1	Introduction	273
	13.2	Structure of Co-simulation	274
	13.3	Co-simulation Semantics	278
	13.4	Adding Fault Injection Semantics to the Co-simulation	283
	13.5	Semantics of the CSL	285
	13.6	Conclusion	291
14	From	Embedded to Cyber-Physical Systems:	
	Challe	enges and Future Directions	293
	John F	Sitzgerald, Peter Gorm Larsen, and Marcel Verhoef	
	14.1	Introduction	293
	14.2	The Co-modelling and Co-simulation Landscape	295
	14.3	Co-modelling in the CPS Design Flow	297
	14.4	Enabling Collections of DE and CT Models to Be Combined	298
	14.5	Open Co-simulation	298
	14.6	Ubiquitous and Distributed Computing	299
	14.7	An Open and Lively Research Field	301
	14.8	Conclusion	302
A	20 cin		305
A	20-sim Summary		303
	A.1	Introduction	305
	A.1 A.2		
	A.2 A.3	Overview	306
		Graphical Models	307
	A.4	Equation Models	307
	A.5	Modelling Tools	307
	A.6	Simulation	308
	A.7	Analysis	309
	A.8	Scripting	310

Contents xix

	A.9	Co-simulation	310
	A.10	Code Generation	310
В	VDM-	RT Language Summary	313
	Peter Gorm Larsen		
	B.1	Operators for Basic Types	313
	B.2	Operators for Set Types	313
	B.3	Operators for Sequence Types	313
	B.4	Operators for Mapping Types	315
	B.5	Record Types and Values in VDM	315
	B.6	Small VDM-RT Examples	316
	B.7	Threads and Synchronisation in VDM	319
	B.8	The System Class Concept in VDM-RT	319
	B.9	Example of Classes	320
	B.10	UML Diagrams	321
C	Design	n Patterns for Use in Co-modelling	323
	_	Samble, Kenneth Pierce, John Fitzgerald, Bert Bos,	
	and M	arcel Verhoef	
	C.1	Introduction	323
	C.2	Controller Patterns	324
	C.3	Fault Patterns	341
	C.4	Fault Tolerance Patterns	347
D	Abstr	act Modelling of ChessWay Safety	359
		el Verhoef and Bert Bos	
Rei	ferences	S	371
Glo	ossary .		377
Inc	lex		381